DTU Library

UniTTe – MC1 - Nordtank Measurement Campaign (Turbine and Met Masts)

Vignaroli, Andrea

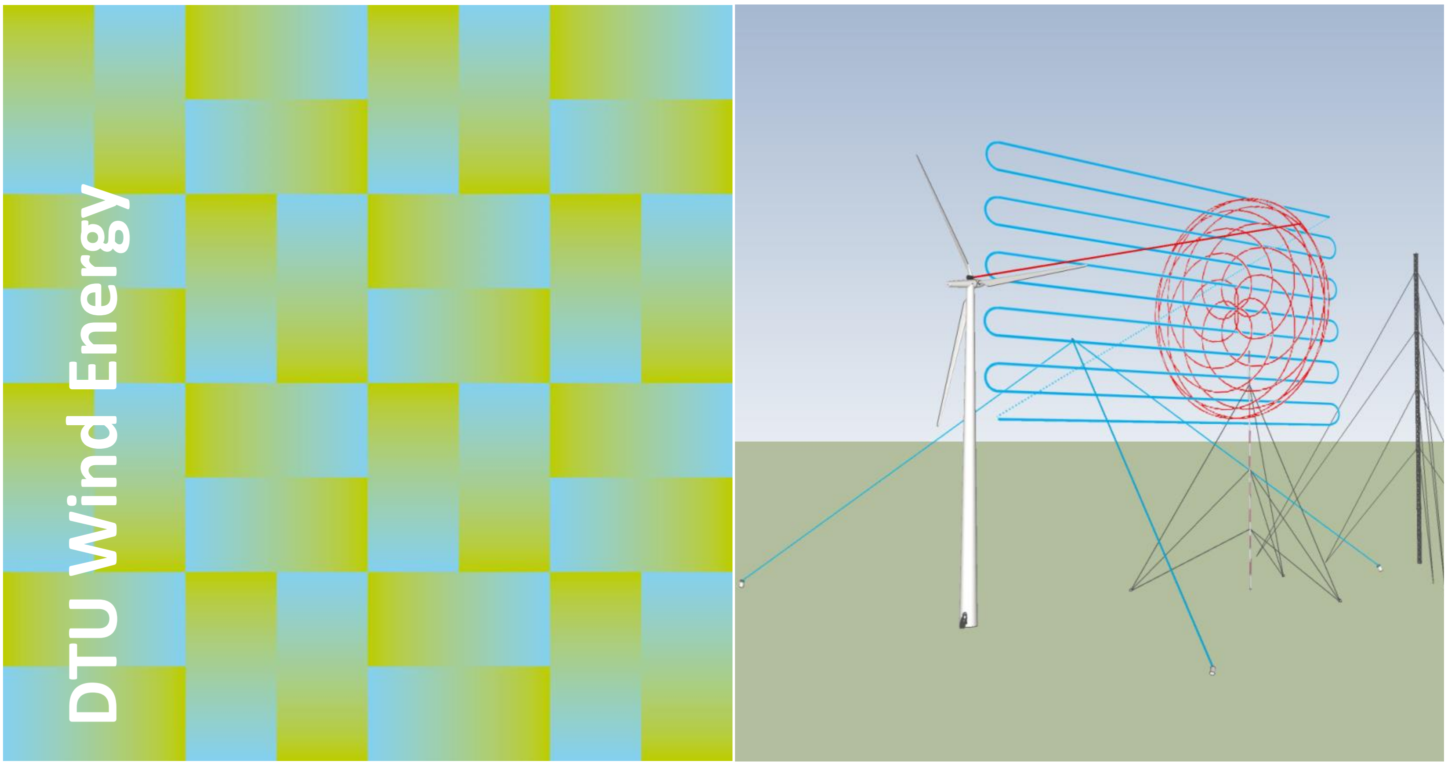
Publication date:
2016

Citation (APA):
Vignaroli, A. (2016). *UniTTe – MC1 - Nordtank Measurement Campaign (Turbine and Met Masts)*. DTU Wind Energy. DTU Wind Energy I No. 0363

UniTTe

Innovation Fund Denmark
RESEARCH, TECHNOLOGY & GROWTH

UniTTe – MC1 - Nordtank Measurement Campaign (Turbine and Met Masts)



Andrea Vignaroli

DTU Wind Energy Report-I-0363

May 2016

DTU Wind Energy
Department of Wind Energy

Author: Andrea Vignaroli

Title: UniTTe – MC1 - Nordtank Measurement Campaign (Turbine and Met Masts)

Institute: Wind Energy

Resume (mask. 2000 char.):

This report describes the instrumentation of the turbine and met masts used in the first measurement campaign of the UniTTe project.

May 2016

Contract no.: Innovationsfondens 1305-00024B

Project: UniTTe
http://www.unitte.dk/

Funding:
Innovation Fund Denmark

Pages:
Tables:
Figures:
References:

Technical University of Denmark
DTU Wind Energy
Risø Campus
Frederiksborgvej 399
DK-4000 Roskilde
Denmark

www.vindenergi.dtu.dk

Preface

This report is a deliverable (D3.11) of the UniTTe project. It describes the setup of the first measurement campaign (MC1) regarding the met masts and wind turbine measurements during the period where measurements were taken with the short range WindScanner and the SpinnerLidar. Set up and measurements with the remote sensing instruments are described in another report (D3.12). Analysis of the data is the focus of several other publications within the project. The purpose of these two reports is to provide the necessary information about the measurements for the data analysis.

Content

1. Introduction

The UniTTe project addresses the question of how best to characterize the wind when measuring the power and loads on modern wind turbines through several measurements campaigns [www.UniTTe.dk]. The first experiment took place on the Nordtank NTK 500/41 wind turbine situated at DTU Risø Campus. The primary purpose of this measurement campaign was to measure the inflow to the Nordtank wind turbine with the short range WindScanner and the SpinnerLidar. The set up and configuration of those instruments are described in [1]. The second purpose was to assess the value of the spinner lidar measurements for the turbine loads assessment.

The turbine is equipped with an extensive number of sensors monitoring and recording the mechanical loads and acceleration on structure and components which have been recorded almost continuously during the years. A detailed description of the sensors, acquisition system and history of the turbine is given in [2].

2. Experiment setup

The wind turbine is geographically located at the Risø Campus, about 6 km North of Roskilde as shown on Figure 1**Error! Reference source not found.**. The wind turbine is placed on the foundation no 4, in a rather gentle sloping terrain towards the area 'Bløden' on the west side of the Roskilde firth. The free undisturbed inflow is from the dominant westerly wind direction.

The test wind turbine is a traditional Danish three-bladed stall regulated Nordtank, NTK 500/41 wind turbine – see specifications in Table 1. Figures in brackets reflect results from post survey on turbine specs.

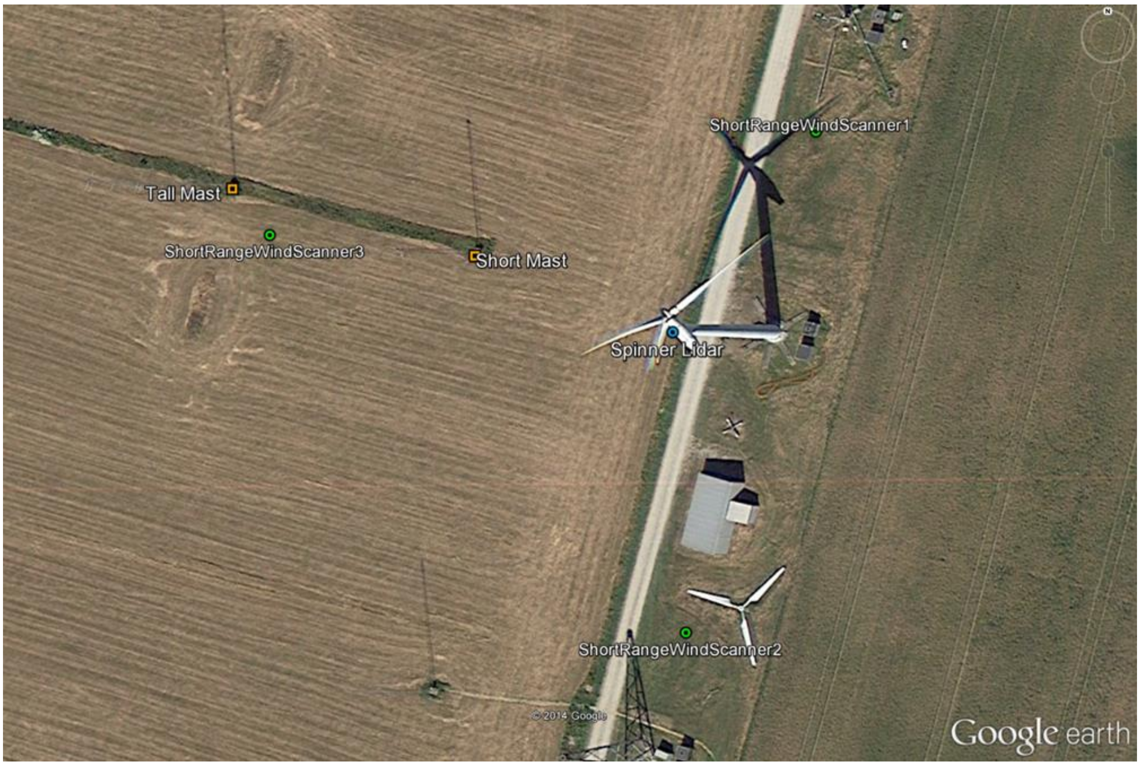


Figure 1 Aerial view of experiment setup

Table 1 Tubine specifications

Rotor Diameter	**41.1m**
Swept area	1320 m²
Rotational Speed	27.1 rpm
Measured tip angle	-0.2º±0.2º
Tilt	2º
Coning	0º
Blade type	LM 19.1
Blade profile[s]	NACA 63-4xx & NACA FF-W3, equipped with vortex generators
Blade length	19.04 m
Blade chord	0.265 – 1.630 m
Blade twist	0.02 – 20.00 degrees
Air brakes	Pivotal blade tips, operated in FS-mode
Mechanical brake	High speed shaft, operated in FS-mode
Power regulation	Passive aerodynamic stall
Gearbox	Flender; ratio 1
Generator	Siemens 500 kW, 4 poles, 690 V
Tower Type	Conical steel tube, h=33.8 m
Hub height	36.0 m
Blade weight	1960 kg (2249 kg incl. Extender and bolts)

Rotor incl. Hub	9030 kg (9846 kg)
Tower head mass	24430 kg (25246kg)
Tower mass	22500 kg

The turbine is primarily used for energy production and tests and it is serviced on commercial conditions. The turbine was installed in 1992 with a 37 m diameter rotor, which in 1994 was substituted with a 41 m diameter rotor in combination with a rotor speed reduction to limit the power output.

Some relevant geometrical properties of the turbine were derived by measuring the position in space of certain points. Such measurements was performed using a theodolite, which is

a surveying instrument with a rotating telescope for measuring horizontal and vertical angles capable to measure distances with an accuracy of in the range of 1 mm. A graphical representation of such measurements can be seen in Figure 2 below followed by the numerical values in **Table 2**

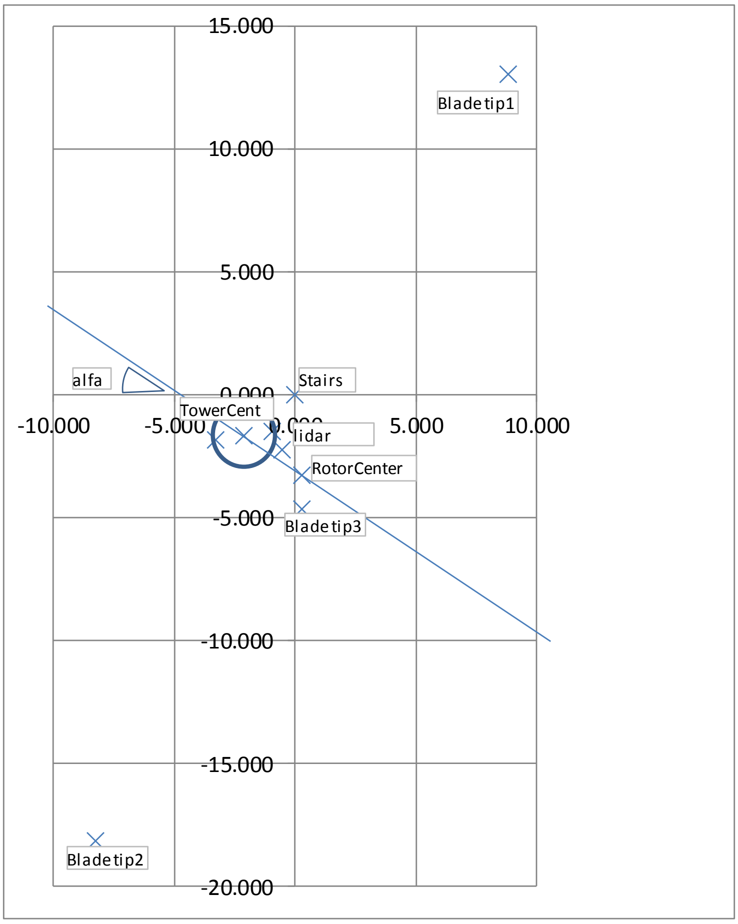


Figure 2 XY Measurements point taken with a theodolite of the Nordtank turbine.

	N	E	Z
Reference_(stairs)	0.000	0.000	0.000
Tower1	-1.514	-0.952	1.754
Tower2	-1.852	-3.264	1.740
tower center	-1.683	-2.108	1.747
Bladetip1	-18.159	-8.266	46.025
Bladetip2	13.033	8.805	43.939
Bladetip3	-4.621	0.283	14.089
Rotor center	-3.249	0.274	34.684
NacLidarLowerleftleftside	-2.250	-0.545	36.062
NacLidarUpperleftleftside	-2.246	-0.566	36.803
alfa (deg)	33.322		
horizontal distance lidar-rotorcenter	**0.980**		
vertical distance lidar-rotorcenter	**1.748**		

rotor tilt	**0.754**	**2.1**
horizontal distance reference-towercenter	2.697	
horizontal distance rotorcenter-towercenter	2.851	
Horizontal distance reference-rotorcenter	**0.153**	

Table 2 Geometrical measurements of the Nordtank Turbine relevant for the project. if not specified, all units in meters

Presently the experimental facility is instrumented as described in the following.

A meteorological mast is placed 2.5 (92.4m) rotor diameters in westerly direction (283°) from the wind turbine. The mast is equipped for measurement of wind speed over the turbine rotor, wind direction, air temperature, air barometric pressure and air humidity (Figure 3) Wind speed is measured by cup anemometers and sonic anemometers that are able to measure the 3D wind vector allowing measuring also wind direction. No wind vanes are present.

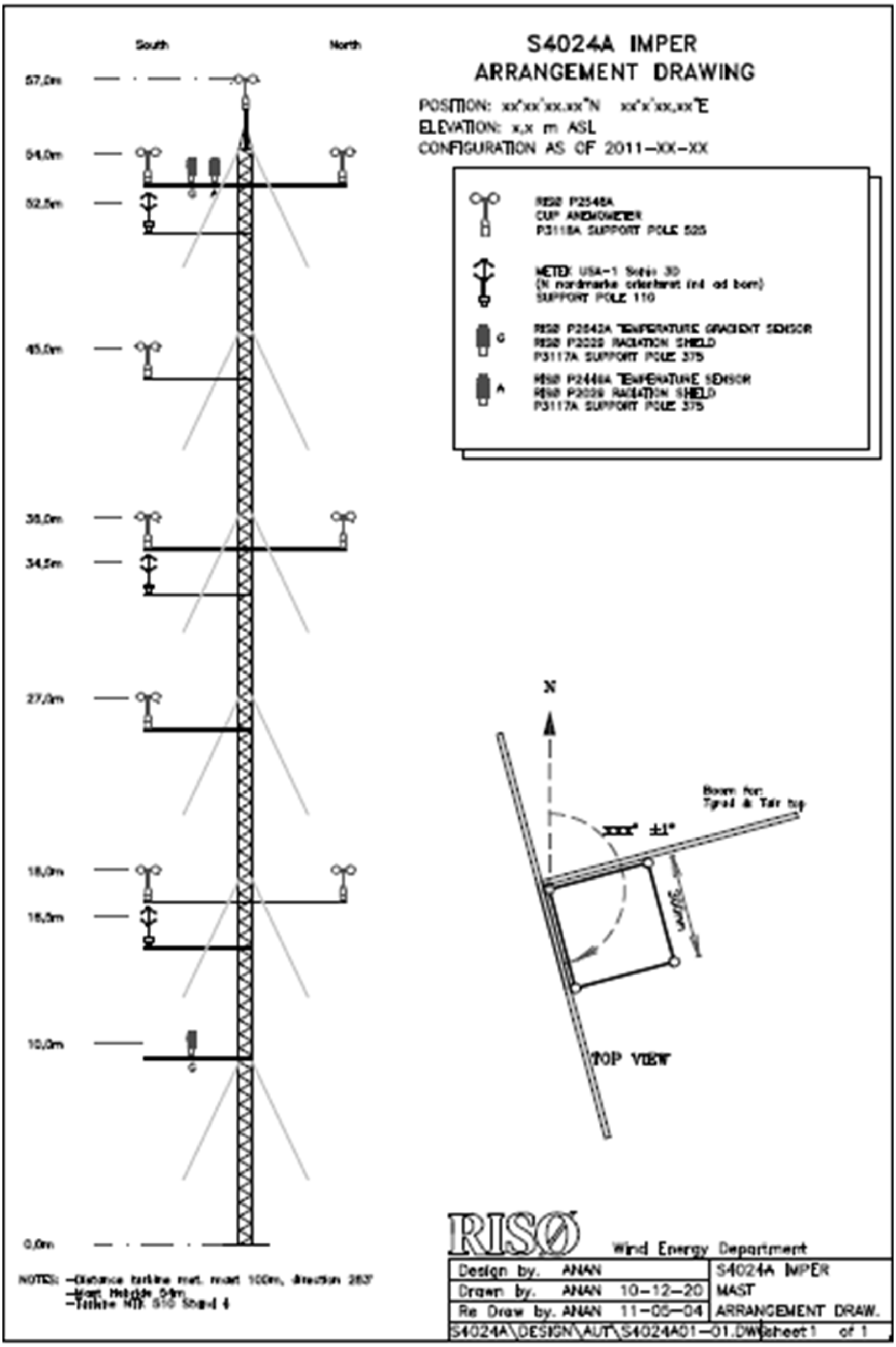


Figure 3 Tall mast

All cup anemometers are WindSensor P2546A type and recently calibrated from Deutsche WindGuard. The information regarding the calibrations for the cup anemometers are reported in the table below (Table 3):

Table 3 Calibration information

Height (m)	Mounting	Serial Number	Calibration date
18	North	2756 DTU-Vea 2076	15.07.2013
18	South	10103 - 2513	17.02.2014
27	South	10095 - 2527	18.06.2014
36	North	13861 - 2759	17.02.2014
36	South	13862 - 2760	17.02.2014
45	South	13863 - 2761	06.11.2013
54	North	14104 DTU-Vea 2790	16.07.2013
54	South	14107 DTU-Vea 2793	16.07.2013
57	Top mounted	14108 DTU-Vea 2794	15.07.2013

The installation is made in accordance with the recent IEC recommendations for both power performance [4] and structural load measurements [5].

There is also another shorter met mast between turbine and the taller mast (at 48.7m from the turbine). This is an older mast that was installed for turbine testing on smaller turbine not existing anymore. The short met mast has been equipped for this experiment with a METEK 3D ultra sonic anemometer (model: scientific/ former USA-1) on the top.

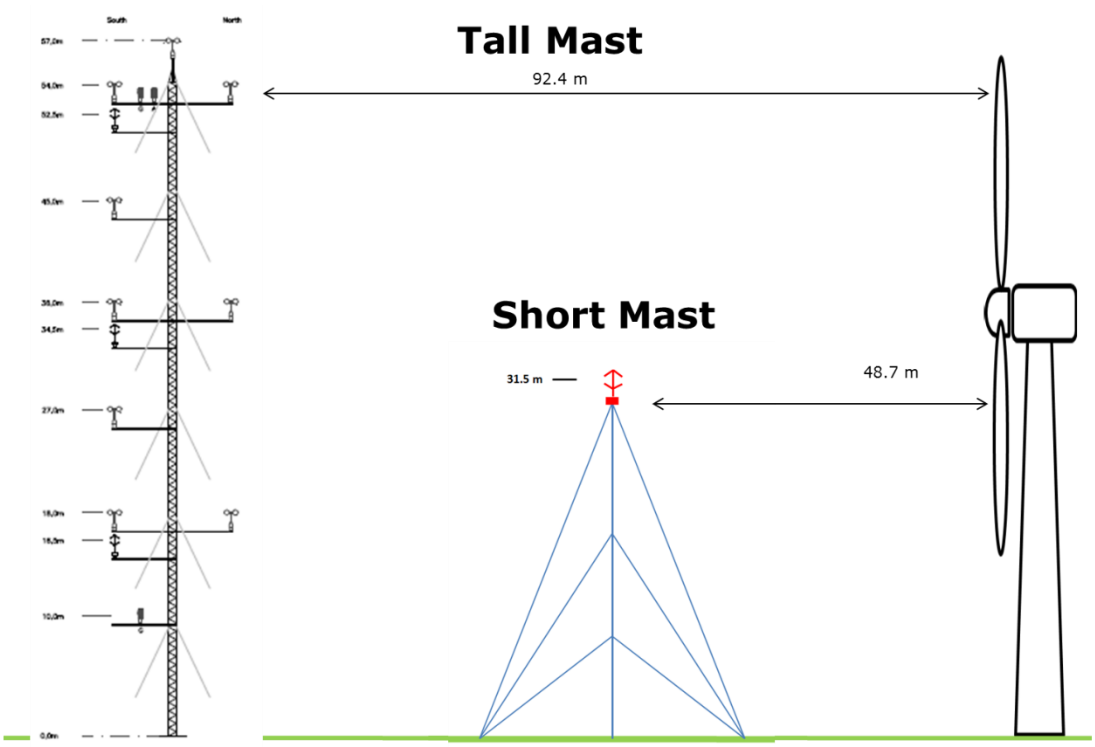


Figure 4 Setup for meteorological measurements

The structural loads on the turbine are monitored by strain gauges mounted at the blade root, on the main shaft, at the tower top and at the tower bottom (**Error! Reference source not found.**) since 2010. The load ignals from the blades include flapwise and edgewise bending moments at the blade root, measured by strain gauges mounted on the blade root steel extenders. The gauge installation at 2.1m from rotor axis enables measurements of both flap-wise and edge-wise bending moments in the rotating right handed reference system of the rotor where the center of the rotor plane is the origin, the x-axis is the rotor axis of rotation and z-axis is aligned with blade n.1. flapwise moment is therefore referred as My and edgewise moment as Mx. The rotor is in 0-position when blade 1 is pointing vertically upwards. A sketch of one of the three blades with the position of the strain gauges I shown in Figure 5.

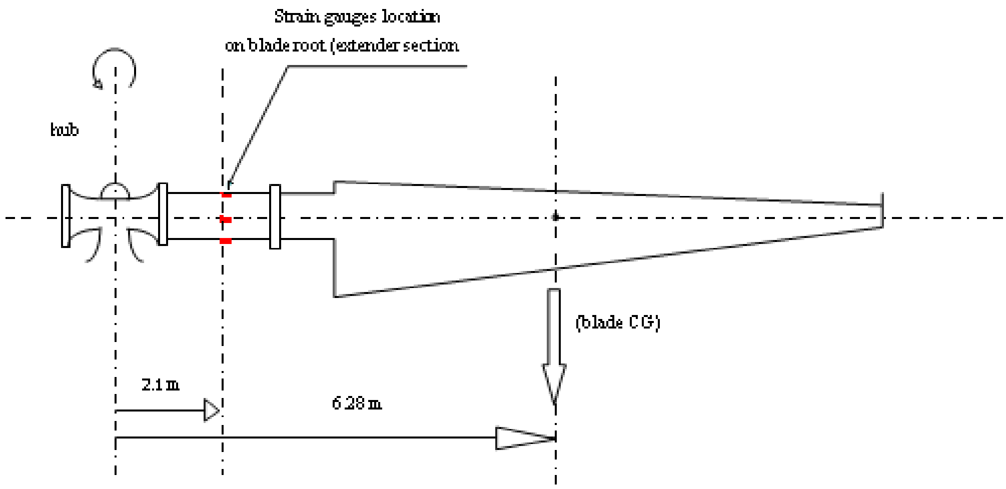


Figure 5Structural load measurements in the blade root

The load measurement on the main shaft includes a torque sensor in front and right after the main bearings, and two bending moments at a position behind the hub/main shaft flange – in a rotating reference system (Figure 7). The gauge location enables measurements of bending moments in two directions, perpendicular to each other in a rotating reference system. The two bending moments combined with the rotor position are used to determine the rotor bending moments in yaw and tilt direction - in a nacelle reference system.

Additionally accelerometers are positioned on the gearbox and on the rear of the nacelle frame.

The tower loads includes torque at the tower top and bending moments in two directions at the tower bottom at 3.5 m from the ground, as shown on in a (fixed) tower reference system (East West refers to the turbine-mast direction and North-South to the direction oriented 90 degrees to the previously defined E-W). The angle between N-S direction and the geographical North is 15.37 Degrees.

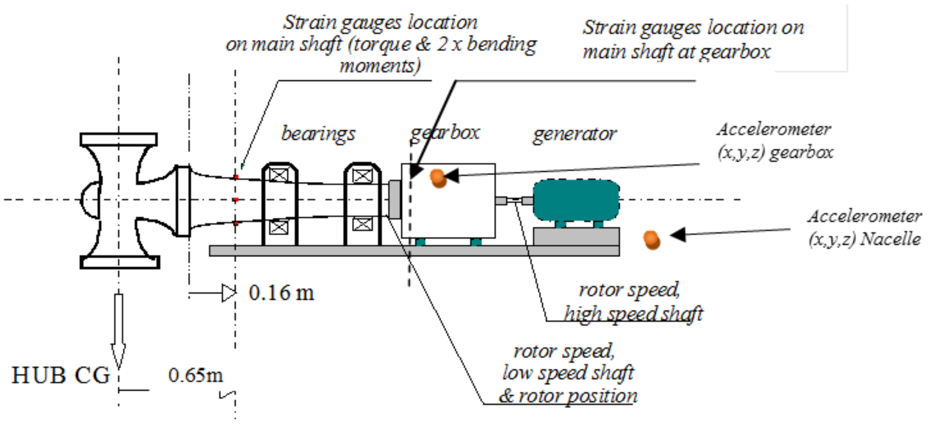


Figure 6 Structural load measurements on the main shaft including distances from the rotor plane.

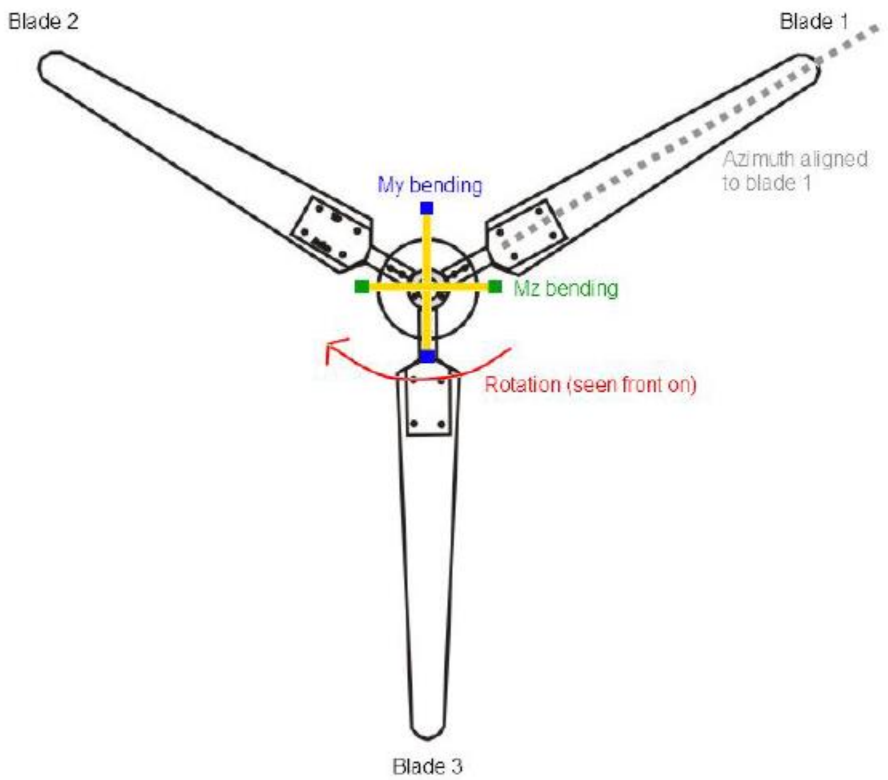


Figure 7 Rotating reference system for load measurements on the shaft.

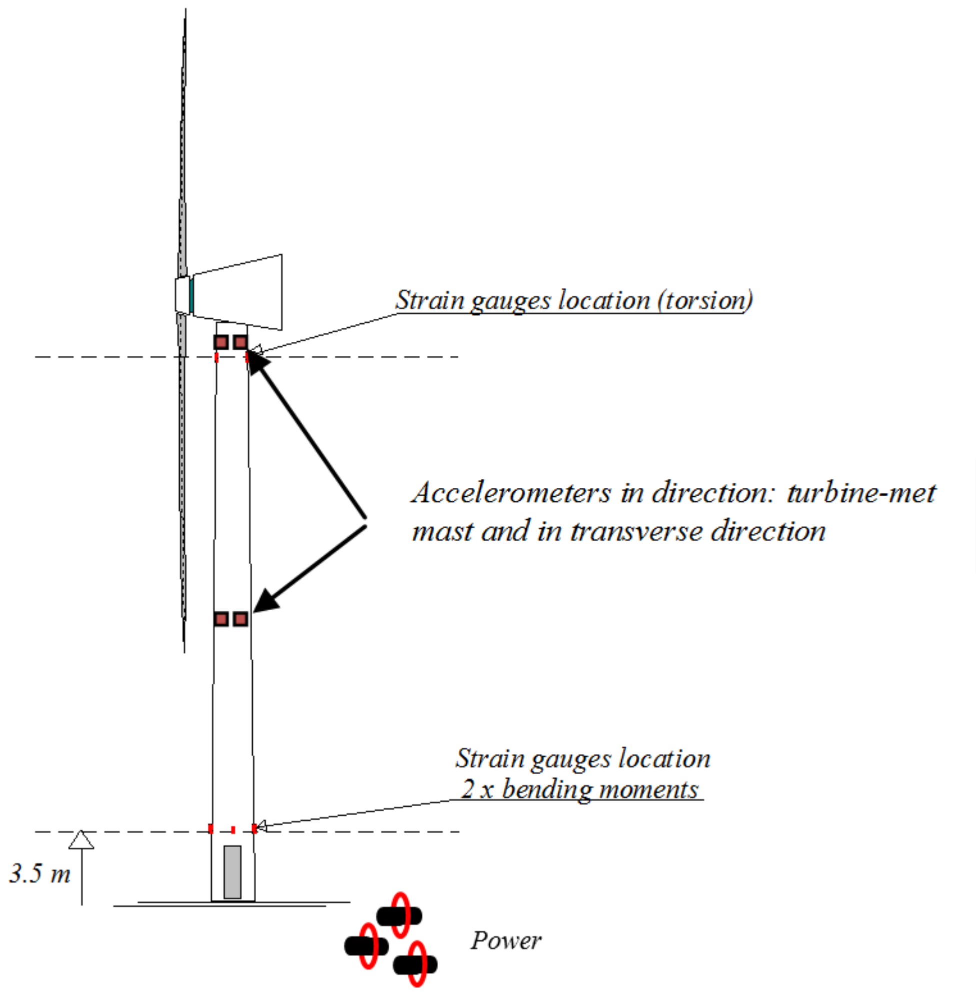


Figure 8 Power and structural load measurements on the welded tubular steel tower

A PC-based data acquisition system has been designed to monitor and collect data from the wind turbine sensors.

The output signals from all sensors are conditioned to the +/- 5 V range. Analogue signals are either continuously varying (strain gauges, temperature…), digital types such as train of pulses (rotational speed, anemometer…) or on/off levels (status signals for brake, blade tips and generator modes). All signals - except outputs from voltage and current transformers - are connected to one of three RISØ P2558A data acquisition units (DAU), each of which provides 16 analogue input channels and 6 general-purpose digital input channels. The analogue inputs are converted into 16-bit quantities. Data from all channels are assembled in a binary telegram, each data occupying 16 bits. The telegram is preceded by two synchronization bytes and it is succeeded by two check-sum bytes. The whole telegram is transmitted to the PC over a RS232 serial channel at a rate of 38400 Baud. The sampling rate at the DAUs is set to 35 Hz so new telegrams are created and send 35 times per second per channel. One DAU is installed in the bottom of the wind turbine tower, another in the nacelle and the last one is mounted on the hub – it is rotating and transmitting data over a RF-link.

The serial channel from each DAU is connected to the PC over a multi-port serial plug-in board. Even a 35 Hz scan rate is high when considering meteorological conditions, but appropriate for mechanical phenomena, and it is far too slow when studying the impact of the wind turbine on the power grid or mechanical loading in the drive train. The facility allows switching to a fast scanning system for studying mechanical and electrical interactions, but this is not used here.

The data acquisition system is build up around a standard desktop PC and connected to the Internet and thereby to DTU network from where it can be operated remotely. To build up a complete documentation of the wind turbine behaviour, data acquisition is carried out constantly. Dedicated measurement software DaQWin™ has been developed under LabVIEW©. The data streams received on the serial channels from the DAUs are read, error checked and the measured values are derived from the data telegrams. Data are assembled in 10-minutes time series and statistics such as mean, standard deviation, maximum and minimum values are calculated. The whole time series and the statistics – with a time stamp added – are stored on disk in ASCII format.

3. Data inspection and quality check

Both 35Hz data and 10min averages recorded from the sensors installed on the turbine in the last 4 years have been inspected for possible problems. The analysis showed that all sensors are in a reasonably good shape and recording accurately over time except the strain gauges measuring the blade root bending moments. Such data show significant drift overtime and it has been decided to perform a new calibration of the strain gauges. The reason for such drift can be pointed to the installation of the strain gauges on the outside of the blades, which can easily lead to water infiltration due to humidity or rain. It was not possible to mount the strain gauges on the internal surface due to the size of the blade root. Example of fast data and 10 min statistics for relevant structural parameters can be found in the following graphs with the aim of showing how the inspection procedure was carried out. It can be noted that the level of strain measured by a strain gauge is proportional to the loads felt by the wind turbine component where the SG is installed. Such loads are function of wind speed and should be repeatable over time (Figure 9). This is not the case for the strain gauges on the blade root (Figure 11). Similar conclusion can be drawn when looking at 10 minutes averages plotted against wind speed (Figure 12) and power (Figure 13) where time is denoted with colors. The color code represents 10 minutes averages who are measured in the same period (few consecutive days) and it is obtained by means of a counter starting from 1 at the first data of the analyzed dataset and increasing of 1 at each time step.

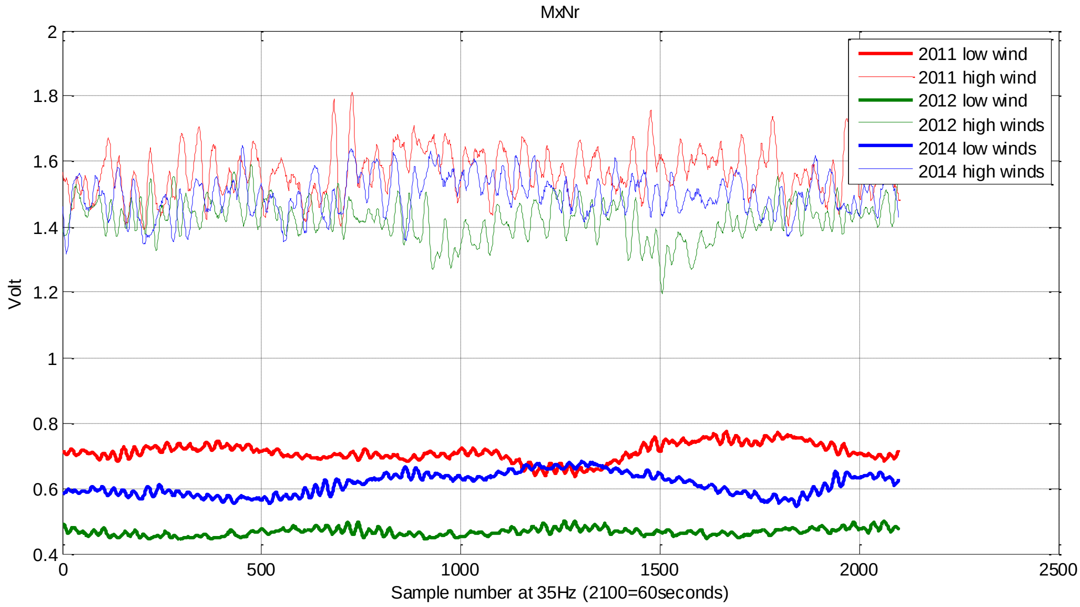


Figure 9 One minute of shaft torsion 35 Hz data in different years and at different speeds ranges (low wind: Speed <10m/s, high winds: Speed >10 m/s)

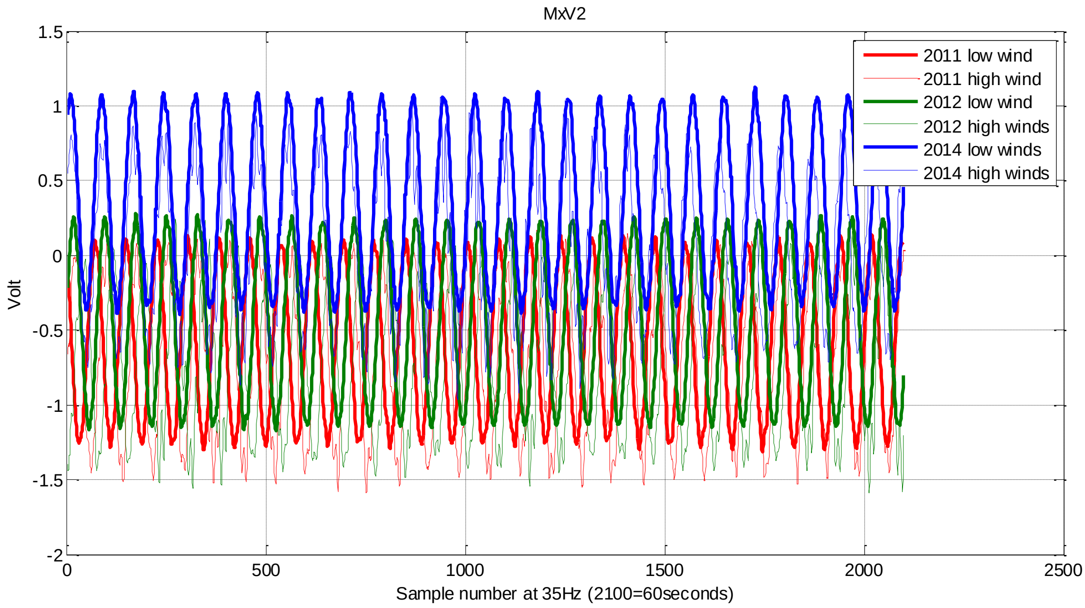


Figure 10 1 minute of Edgewise bending moment 35 Hz data in different years and at different speeds

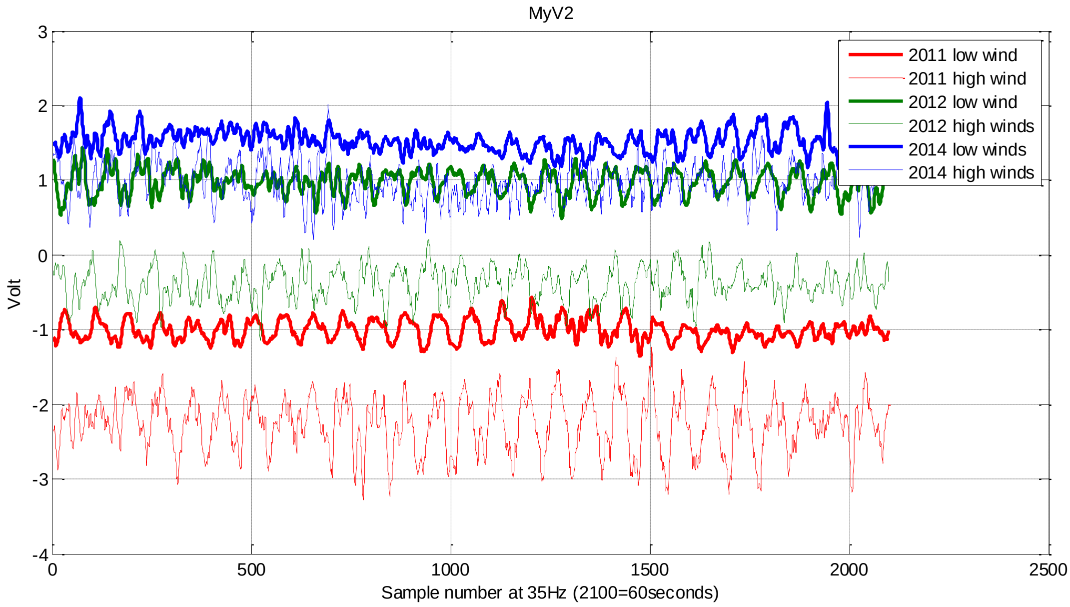


Figure 11 One minute of flap wise bending moment 35 Hz data in different years and at different speeds

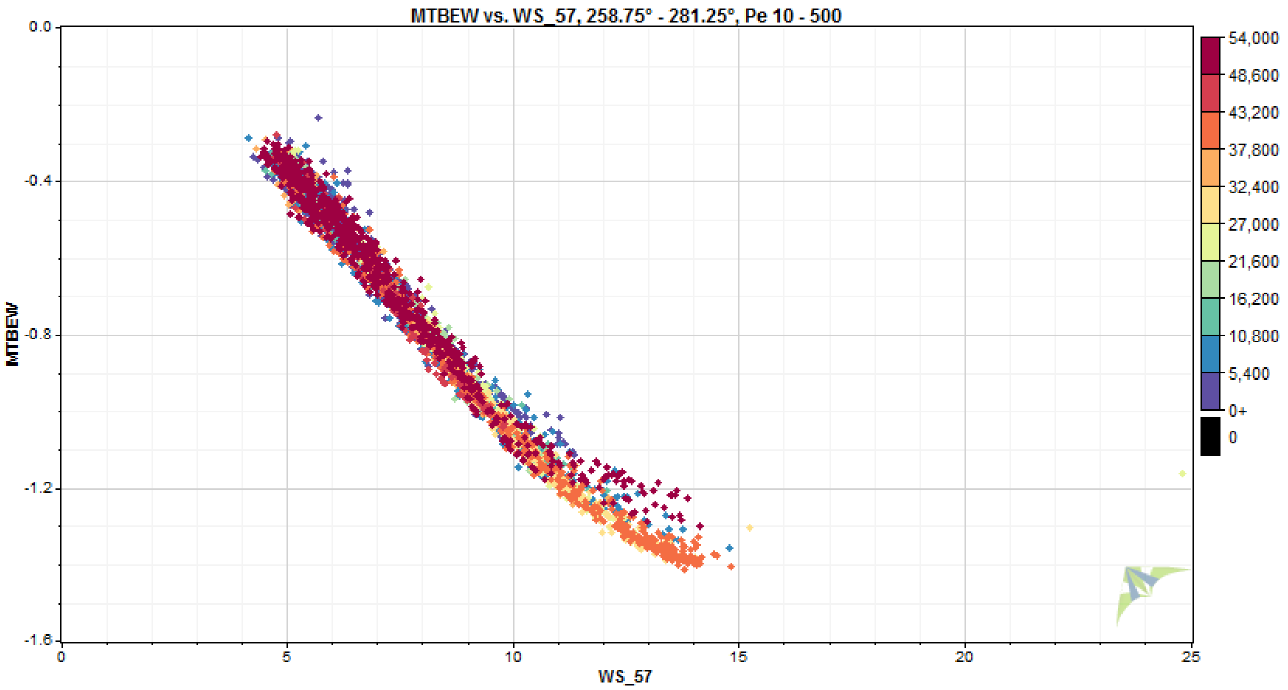


Figure 12 Example of no drift. 10 min averages of tower bottom bending moment East West direction vs wind speed (top cup anemometer at 57m) color coded by time

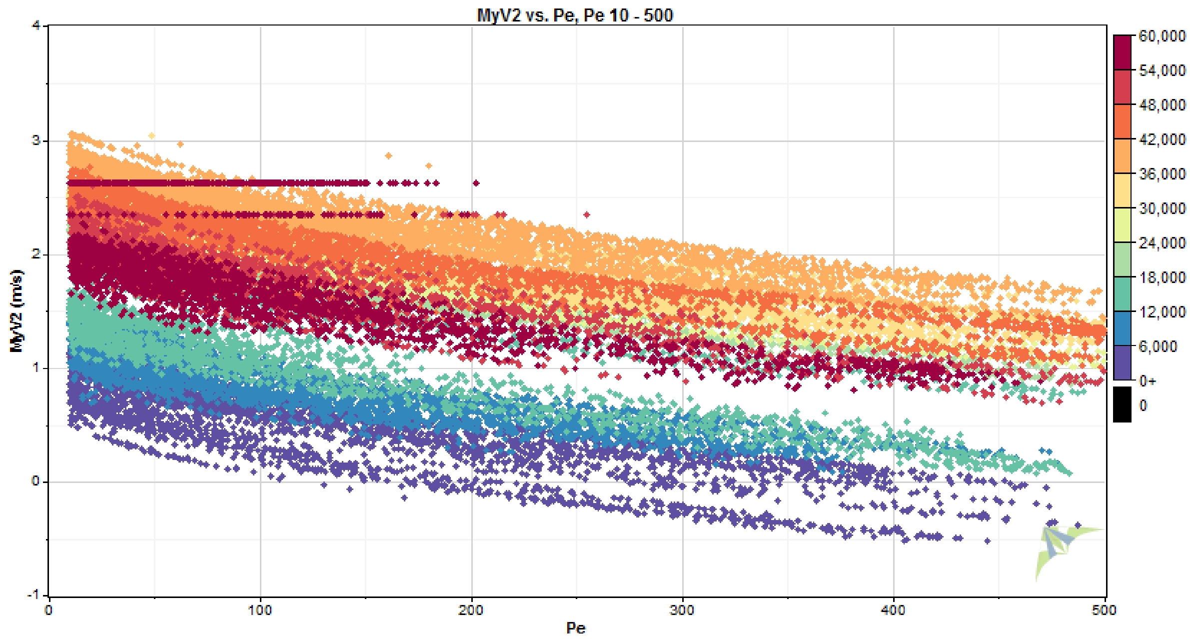


Figure 13 Example of drift: 10 min averages of flap wise blade 2 root moments as a function of power, color coded by time

4. Strain Gauges Calibrations

This section describes the calibration of the blade strain gauge sensors performed from 16th to 17th of July 2014 in order to find the actual coefficients that will allow converting strain in loads. It will be assumed that the drift will be negligible during the short duration of the measurement campaign.

4.1 Line calibration

The transmission line includes the slip rings for the signal transmission of the rotor to the "fixed world", all the transmission cables, amplifiers for the amplification of the signal and the Data Acquisition Unit (DAU). Each line needs to be calibrated in order to verify that it has a linear response.

All channels were calibrated in the following way: the strain gauge signal was disconnected from the measuring device (Tower bending moment NS) and instead a traceable voltage calibration box was connected to it. The signal range of this box is 0mV/V, +/- 0.2 mV/V, +/- 0.4 mV/V,… +/- 2.0 mV/V.

By applying these given signals, and measuring the voltage (V_{out}), the linearity of the channel was determined as can be seen in the results in the table below.

Known Voltage source	Output digitized signal	Output Voltage

-0.9*2mV/V	2414 counts	-4.63V
-0.6*2mV/V	12540 counts	-3.09V
-0.3*2mV/V	22664 counts	-1.54V
-0.0*2mV/V	32789 counts	-0.00V
0.3*2mV/V	42912 counts	1.55V
0.6*2mV/V	53037 counts	3.09V
0.9*2mV/V	63163 counts	4.64V

Table 4 Line calibration results

The load cell was rated 5 tons max and this maximum load corresponds to 2mV/V. The complete range is covered by roughly 65000 counts. After checking the line linearity, it was decided for simplicity to apply the following gain (Column D) and offset (Column E) to DAQwin to monitor kgs instead of Volts.

	A	B	C	D	E	F
1	Kg	Count	Range of counts covered (B2-B3)	gain (A2/C2)	offset amplifier (-B3*D2)	Offset loadcell (from daqwin)
2	2500	50262	16833	0.148518	-4964.80	-4975.5
3	0	33429				

Figure 14 Modification applied to DAQwin for monitoring the output of the load cell in Kg

4.2 Strain Gauge Calibration procedure

For flapwise calibration, the blade was placed vertically downwards and pulled in towards the tower. To achieve this, a sling was attached where the pivoted blade tips are attached to the main blade section. The other end of the sling was attached around the tower itself just above the inspection door (see Figure 15). A loadcell was placed between these two slings, with one end attached to the blade sling and the other end attached to chain connecting it with the tower sling. A ratchet was used to create tension by shortening the length of chain between the tower sling and the loadcell, therefore exerting a force on the blade and pulling it towards the tower. The load applied through a pulling device was measured by the load cell, which was connected to the main measurement acquisition system. The load was applied in 30 seconds long steps of roughly 0.2 kN and the maximal force was about 8 kN and then released in steps again. A final continuous pull and release completed the test (see Figure 17). Repetition of the test to compensate external forces due to the wind was not considered necessary since the wind conditions were ideal (very low wind - cup anemometers were barely rotating).

For the edgewise calibration process, the blade was moved into a horizontal position (see Figure 16) and the load applied vertically with a rope connected to a metal frame bolted on the ground following the previously described stepwise strategy. Horizontality of the blade was assured by checking the verticality of blade root flange through a digital level.

It must be stated that the angles between the pulling rope and the blade are in both cases 90 ° (with an error of no more than 5°). So no correction needs to be applied to the magnitude of the applied load in the desired direction.

This was done for every blade.

Figure 15 Picture of one of the blade being attached to the tower for the flapwise bending moment strain gauge calibration

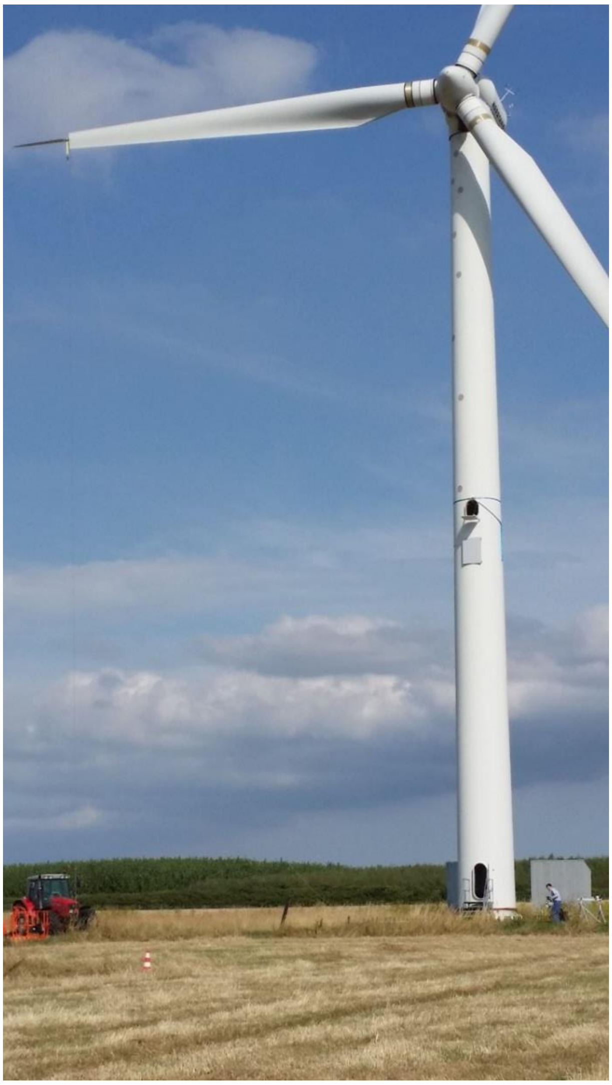


Figure 16 Picture of the blade position (horizontal) for the edgewise bending moment strain gauge calibration

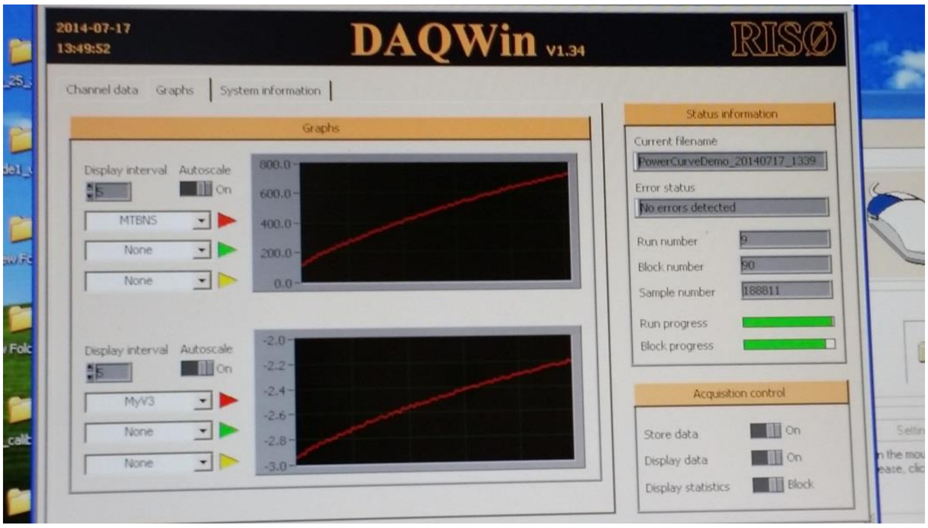


Figure 17 Screenshot of DAQwin Software during continuous pull. The first graph shows the applied load in Kg and below the correspective output from the strain gauge in Volt, both over time.

4.3 Regression analysis

It is important to note that the horizontal axis is in [Volt] units, while the vertical axis (loading) is in [kg]. To obtain the bending moments in [Nm] we need first to multiply the output in kg with the acceleration of gravity (9.81 m*s^-2) and with the distance between the strain gauges and the point where the load was applied (15.82m).

The regression analysis for the edgewise and flapwise moment of blade n1 are reported in the figures below as example. The other two blades show a very similar behavior.

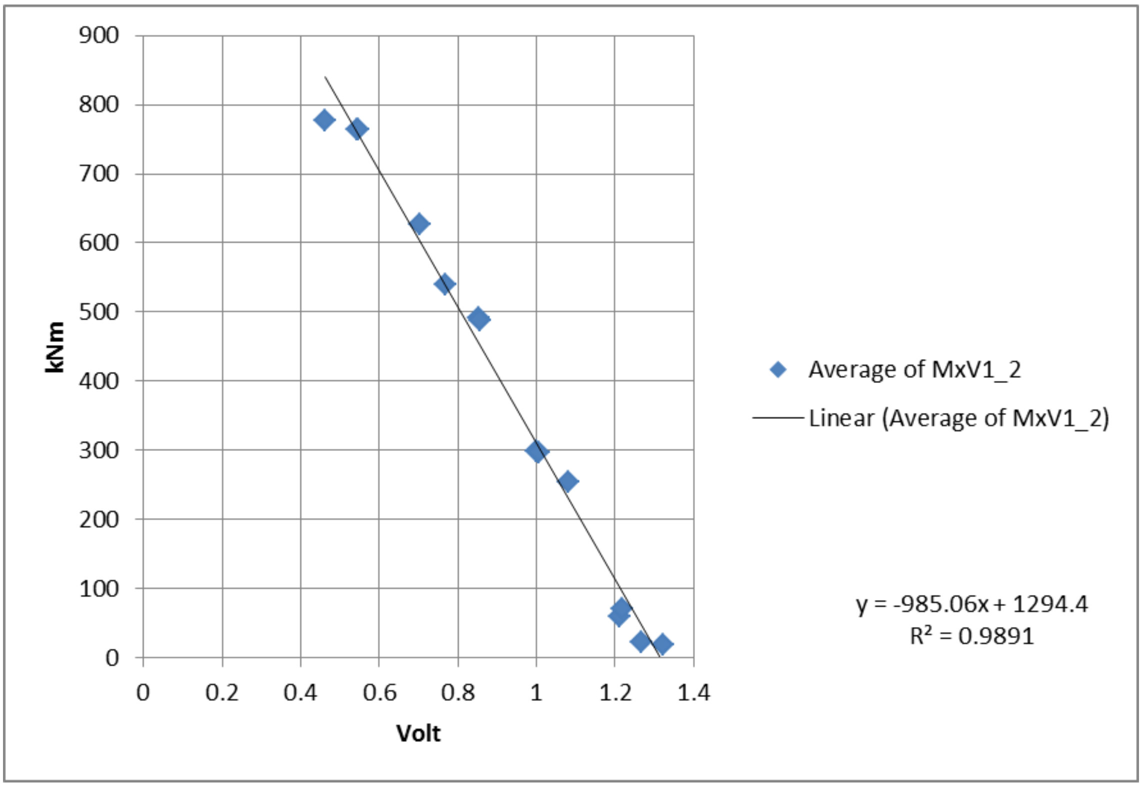


Figure 18 Blade 1 Edgewise applied moment (y) against measured strain (x)

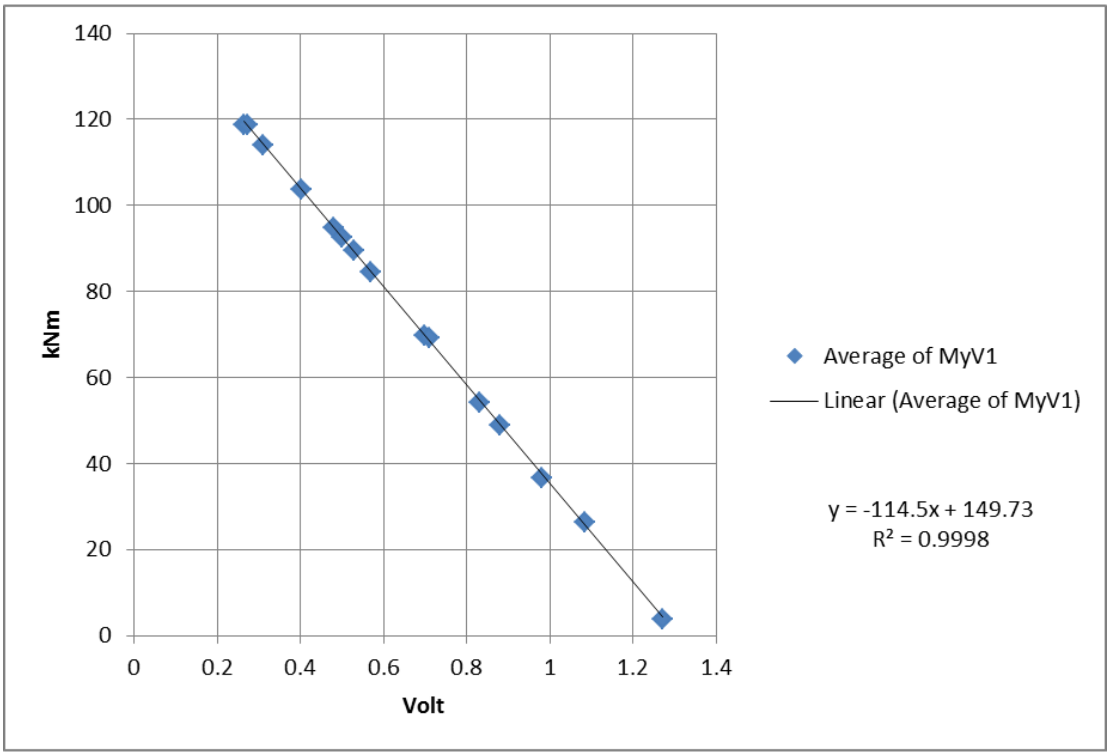


Figure 19 Blade 1 Flapwise applied moment (y) against measured strain (x)

4.4 Zero determination

The offsets calculated from the regression analysis do not accurately represent a *real* zero-loading situation for a number of reasons like non-zero wind at the time of the experiment, the presence of a coning angle, etc.

The next figures illustrate the sinusoidal response of the strain gauges for an *idling* of the turbine rotor (Figure 20 and Figure 21). By this procedure the real zero point of each strain gauge can be determined. It can be seen that all strain gauges show non-zero behavior.

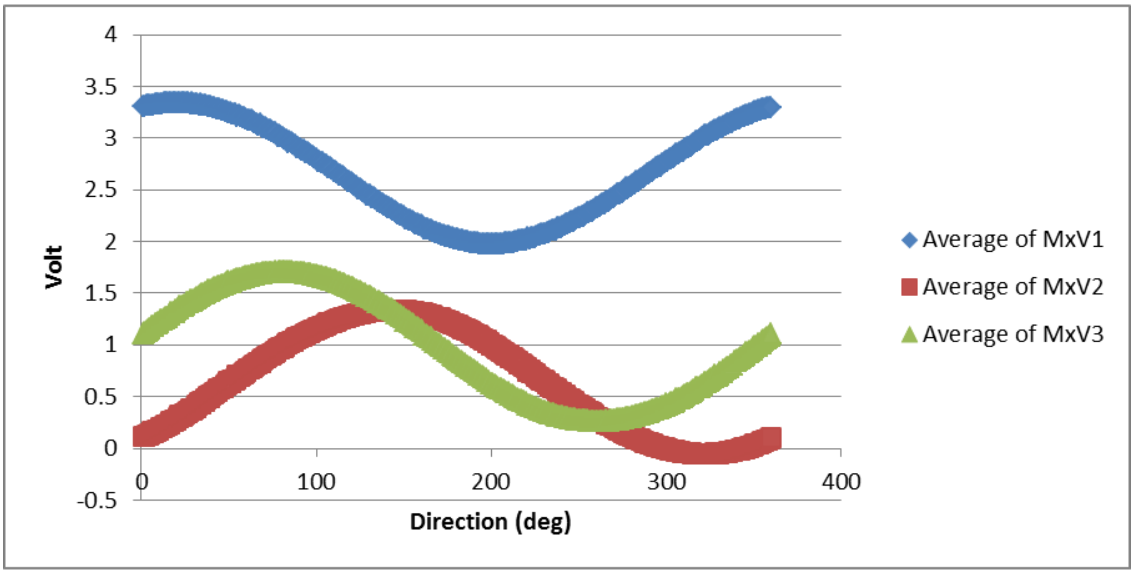


Figure 20 Edge wise moment during a full idling rotation of the rotor. The x axis is the azimuth position of blade 1

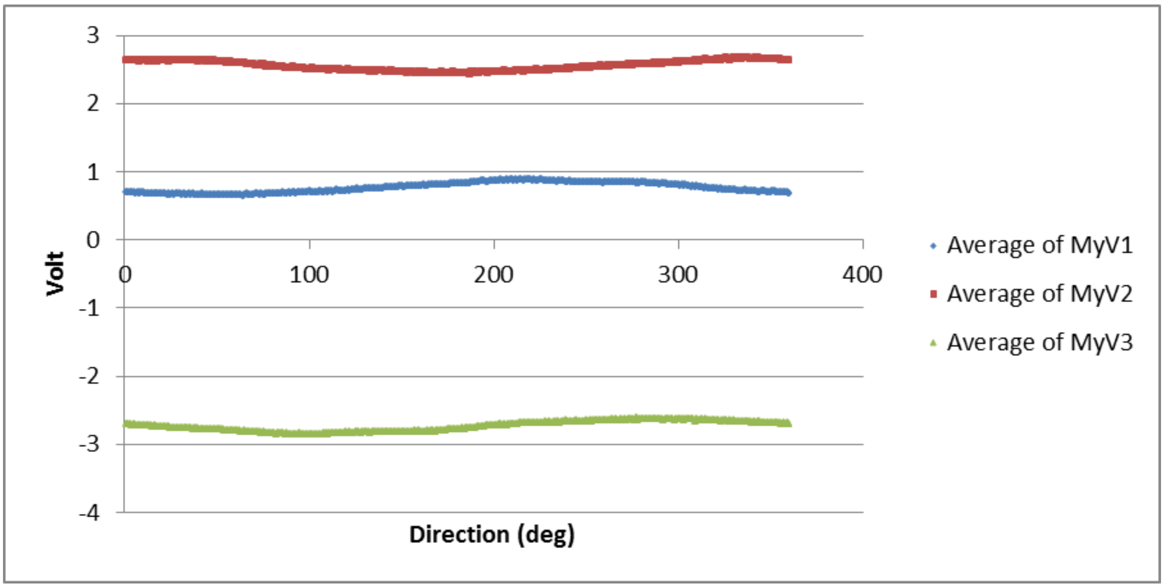


Figure 21 Flapwise moment during a full idling rotation of the rotor

4.5 Results

The following values have been used to calibrate the measured signals from volt to kNm. Values in “Gain” column and “Zero Idling” columns are used. The values in the other columns are reported for comparison.

Table 5 Calibration results

	gain (kNm/V)	offset (kNm)	Zero idling (V)	Zero idling (kNm)
MxV1	-152.88	200.88	2.66	406.64
MyV1	-114.50	149.73	0.77	88.14
MxV2	-173.74	-33.58	0.64	111.54
MyV2	-117.17	303.96	2.55	299.15
MxV3	150.54	46.10	0.98	-148.22
MyV3	127.39	392.58	-2.74	349.03

5. Database

All data are stored in a MySQL database, named Nordtank, on Veadbs03 server. 10 min statistics can be found in tables named calmeans, calmaxs, calmins, calstdvs and calmeans_loads, calmaxs_loads, calmins_loads. The first 4 tables contains 10 minutes periods averages, max value in the ten minute period, min value in the ten minute period and standard deviation respectively of turbine and mast parameters that has been already calibrated during the data acquisition. The latter 4 tables contain 10 min statistics of parameters that were recorded in Volt and have been converted in physical values with the calibration values from Table 5.

The 35Hz raw data (before calibration, therefore loads are given in volts) can be found in the monthly tables caldata_2014_07_35hz, caldata_2014_08_35hz, caldata_2014_09_35hz and caldata_2014_10_35hz Due to limitations of the database it was not possible to create table containing all calibrated values at 35Hz. The parameters that show a slope different than 1 and an offset different than zero in the Channel list table (thus are not calibrated in the database) can be retrieved using the following query:

```
SELECT

Name,

scan_id,

Mz_TT*1136.1+840 as Mz_TT,

MTBEW*5424+158 as MTBEW,

MTBNS*5114.9+528 as MTBNS,

MxNR*193.2-87 as MxNR,

MyNR*79.45+23 as MyNR,

MzNR*86.66-245 as MzNR,

MxV1*-152.88+412 as MxV1,

MyV1*-114.5+77 as MyV1,

MxV2*-173.74+114 as MxV2,

MyV2*-117.17+287 as MyV2,

MxV3*-150.54+147 as MxV3,

MyV3*+127.39+337 as MyV3,

Acc_Gearx*2.212389-4.86062 as Acc_Gearx,

Acc_Geary*2.267574-5.38549 as Acc_Geary,

Acc_Gearz*2.257336-5.17381 as Acc_Gearz,
```

```
Acc_Nacx*2.227171-4.70379 as Acc_Nacx,

Acc_Nacy*2.217295-4.19734 as Acc_Nacy,

Acc_Nacz*2.309469-4.65127 as Acc_Nacz,

TBAcc_x1*2.212389-4.77655 as TBAcc_x1,

TBAcc_y1*2.227171-7.34967 as TBAcc_y1,

TBAcc_x2*2.207506-5.85872 as TBAcc_x2,

TBAcc_y2*2.325581-5.97674 as TBAcc_y2

FROM nordtank.caldata_2014_08_35hz where Name >='201407010000'
```

6. Channel List in MySQL database

Name	Gain	Offset	Unit	description
HH	–	–	–	Hour of measurement from windows clock
MM	–	–	–	Minutes of measurement from windows clock
SS	–	–	–	Seconds of measurement from windows clock
Mz_TT	1136.1	840	kNm	Tower top torsion, h
MTBEW	5424	158	kNm	tower bottom bending moment , direction Turbine - mast
MTBNS	5114.9	528	kNm	tower bottom bending moment perpendicular to MTBEW
Pe	1	0	kW	Active power
IO_tip	1	0	0/1	Tip activated (0/1, 1=active)
IO_brk	1	0	0/1	Brake activated (0/1, 1=active)
IO_gen	1	0	0/1	Generator grid conn. (0/1, 1=active)
Yaw	1	0	Deg	NP- nacelle position
Rot_Azi_Pos	1	0	Deg	Azimuth, top=0
Rot_Speed_slow	1	0	rpm	Rotor speed main shaft
Rot_Speed_fast	1	0	rpm	Rotor speed generator shaft
WS_Nac	1	0	m/s	WSN - nacelle wind speed
WD_Nac	1	-180	Deg	WDN - nacelle wind direction
MxNR	193.2	-87	kNm	Torque, main shaft
MyNR	79.45	23	kNm	BM main shaft MYNR
MzNR	86.66	-245	kNm	BM main shaft MZNR
MxV1	-152.88	412	kNm	B1.Edgewise
MyV1	-114.5	77	kNm	B1.Flapwise
MxV2	-173.74	114	kNm	B2.Edgewise
MyV2	-117.17	287	kNm	B2.Flapwise
MxV3	-150.54	147	kNm	B3.Edgewise
MyV3	127.39	337	kNm	B3.Flapwise
Acc_Gearx	2.212389	-4.86062	[g]	Acceleration Gearbox forth\back
Acc_Geary	2.267574	-5.38549	[g]	Acceleration Gearbox sideway
Acc_Gearz	2.257336	-5.17381	[g]	Acceleration Gearbox up\down
Acc_Nacx	2.227171	-4.70379	[g]	Acceleration Nacelle forth\back
Acc_Nacy	2.217295	-4.19734	[g]	Acceleration Nacelle sideways
Acc_Nacz	2.309469	-4.65127	[g]	Acceleration Nacelle up\down
TBAcc_x1	2.212389	-4.77655	[g]	Tower Acceleration 140 cm from top flange turbine-mast dir
TBAcc_y1	2.227171	-7.34967	[g]	Tower Acceleration 140 cm from top flange transverse dir
TBAcc_x2	2.207506	-5.85872	[g]	Tower Acceleration 80 cm from flange turbine-mast dir
TBAcc_y2	2.325581	-5.97674	[g]	Tower Acceleration 80 cm from flange transverse dir
WS_57	1	0	m/s	WS, h=57 m, windsensor cup anemometer, top mounted ~~boom~~
WS_54_North	1	0	m/s	WS-North, h=54 m , windsensor cup anemometer, boom in north direction
WS_54_South	1	0	m/s	WS-South, h=54 m, , windsensor cup anemometer, boom in south direction
Sstat_M2_52_5	1	0	[-]	Status Sonic@52.5m
SX_M2_52_5	1	0	[m/s]	Speed Vector x-direction@52.5m (sonic anemometer)
SY_M2_52_5	1	0	[m/s]	Speed Vector y-direction@52.5m(sonic anemometer)
SZ_M2_52_5	1	0	[m/s]	Speed Vector z-direction@52.5m(sonic anemometer)
ST_M2_52_5	1	0	[Deg C]	Air temperature Sonic@52.5m(sonic anemometer)

Sspd_M2_52_5	1	0	[m/s]	Speed Sonic@52.5m
Sdir_M2_52_5	1	0	[Deg]	Horizontal wind Direction@52.5m(sonic anemometer)
Stilt_M2_52_5	1	0	[Deg]	Tilt angle 52.5m(sonic anemometer)
WS_45_South	1	0	m/s	WS, h=45 m , windsensor cup anemometer, boom in south direction
WS_36_North	1	0	m/s	WS-North, h=36 m (cup anemometer)
WS_36_South	1	0	m/s	WS-South, h=36 m (cup anemometer)
Sstat_M2_34_5	1	0	[-]	Status Sonic@34.5m
SX_M2_34_5	1	0	[m/s]	Speed Vector x-direction@34.5m(sonic anemometer)
SY_M2_34_5	1	0	[m/s]	Speed Vector y-direction@34.5m(sonic anemometer)
SZ_M2_34_5	1	0	[m/s]	Speed Vector z-direction@34.5m(sonic anemometer)
ST_M2_34_5	1	0	[Deg C]	Air temperature Sonic@34.5m(sonic anemometer)
Sspd_M2_34_5	1	0	[m/s]	Speed Sonic@34.5m
Sdir_M2_34_5	1	0	[Deg]	Horizontal wind Direction@34.5m(sonic anemometer)
Stilt_M2_34_5	1	0	[Deg]	Tilt angle 34.5m(sonic anemometer)
WS_18_North	1	0	m/s	WS-North, h=18 m
WS_18_South	1	0	m/s	WS-South, h=18 m
Sstat_M2_16_5	1	0	[-]	Status Sonic@16.5m(sonic anemometer)
SX_M2_16_5	1	0	[m/s]	Speed Vector x-direction@16.5m(sonic anemometer)
SY_M2_16_5	1	0	[m/s]	Speed Vector y-direction@16.5m(sonic anemometer)
SZ_M2_16_5	1	0	[m/s]	Speed Vector z-direction@16.5m(sonic anemometer)
ST_M2_16_5	1	0	[Deg C]	Air temperature Sonic@16.5m(sonic anemometer)
Sspd_M2_16_5	1	0	[m/s]	Speed Sonic@16.5m(sonic anemometer)
Sdir_M2_16_5	1	0	[Deg]	Horizontal wind Direction@16.5m(sonic anemometer)
Stilt_M2_16_5	1	0	[Deg]	Tilt angle 16.5m(sonic anemometer)
Tabs_54	1	0	deg C	Absolute Air Temp, h=54 m
Tdiff_54_10	1	0	deg C	Differential Temp, 54m - 10m
Pressure_mast	1	0	hPa	Pressure 2m
Sstat_M2_31_5	1	0	[-]	Status Sonic@31.5m - top mounted on short mast
SX_M2_31_5	1	0	[m/s]	Speed Vector x-direction@31.5m - top mounted on short mast
SY_M2_31_5	1	0	[m/s]	Speed Vector y-direction@31.5m - top mounted on short mast
SZ_M2_31_5	1	0	[m/s]	Speed Vector z-direction@31.5m - top mounted on short mast
ST_M2_31_5	1	0	[Deg C]	Air temperature Sonic@31.5m - top mounted on short mast
Sspd_M2_31_5	1	0	[m/s]	Speed Sonic@31.5m - top mounted on short mast
Sdir_M2_31_5	1	0	[Deg]	Horizontal wind Direction@31.5m - top mounted on short mast
Stilt_M2_31_5	1	0	[Deg]	Tilt angle 31.5m - top mounted on short mast
Rain2	1	0	0/1	Rain short mast
gama_Av				yaw missalignment from spinner - 1 probe
beta_Av				flow inclination from spinner -1 probe
gama				yaw missalignment from spinner
beta				flow inclination from spinner
V1				Vspinner
V2				Vspinner
V3				Vspinner
Temp_1				Tspinner
Temp_2				Tspinner
Temp_3				Tspinner
Acc_1				Accelerometer Spinner
Acc_2				Accelerometer Spinner

Acc_3	Accelerometer Spinner
Theta	Rotor position from spinner
rotor_pos	Rotor position from spinner
rotor_speed	Rotor speed from spinner
Speed_Av	Horizontal speed Spinner - 1 probe
speed	Horizontal speed Spinner
Speed_Quality	Quality Spinner Data
Acc_Quality	Quality Spinner Data
Calculation_Quality	Quality Spinner Data
Sstat	Sonic Nacelle
Sheat	Sonic Nacelle
SX	Sonic Nacelle
SY	Sonic Nacelle
SZ	Sonic Nacelle
ST	Sonic Nacelle
Sdir	Sonic Nacelle
Sspeed	Sonic Nacelle
Stilt	Sonic Nacelle
WS_hh	Previous measurements on short mast
T_Air	Previous measurements on short mast
B_Air	Previous measurements on short mast
Shaft_tors2	Shaft torsion in gearbox
Shaft_tors3	Shaft torsion in generator

7. Accuracy on turbine yawing

There was a certain concern that the installation of the spinner lidar on the nacelle of the Nordtank turbine right behind the rotor plane would disturb the wind vane that is used to control the turbine yaw. For this reason some investigations has been undertaken to assess accuracy of direction measurements from yaw and sonic anemometers on mast and detect possible yaw misalignment.

The turbine is equipped with a spinner anemometer. A spinner anemometer is a system comprised of 3 ultrasonic probe mounted on the turbine spinner that allows to sense characteristics of the inflow wind such as speed, temperature and vertical and horizontal inclination of relative to the rotational axis of the rotor [6].

The horizontal angle between the wind speed vector measured by the spinner anemometer and the rotation axis gama_Av has been plotted against the difference between yaw and direction measured by the sonic anemometer mounted on the tall met mast at hub height (Figure 10).

Figure 10 shows a 10 degrees offset on average when the wind speed is perpendicular to the rotor according to the spinner anemometer (gama_Av=0°).

Plotting instead such difference against wind speed measured at the met mast (Figure 11) shows that large yaw misalignment can happen at low wind speeds (below cut in), but it decreases at higher speeds and stabilizes at the 10 degrees found in the previous plot.

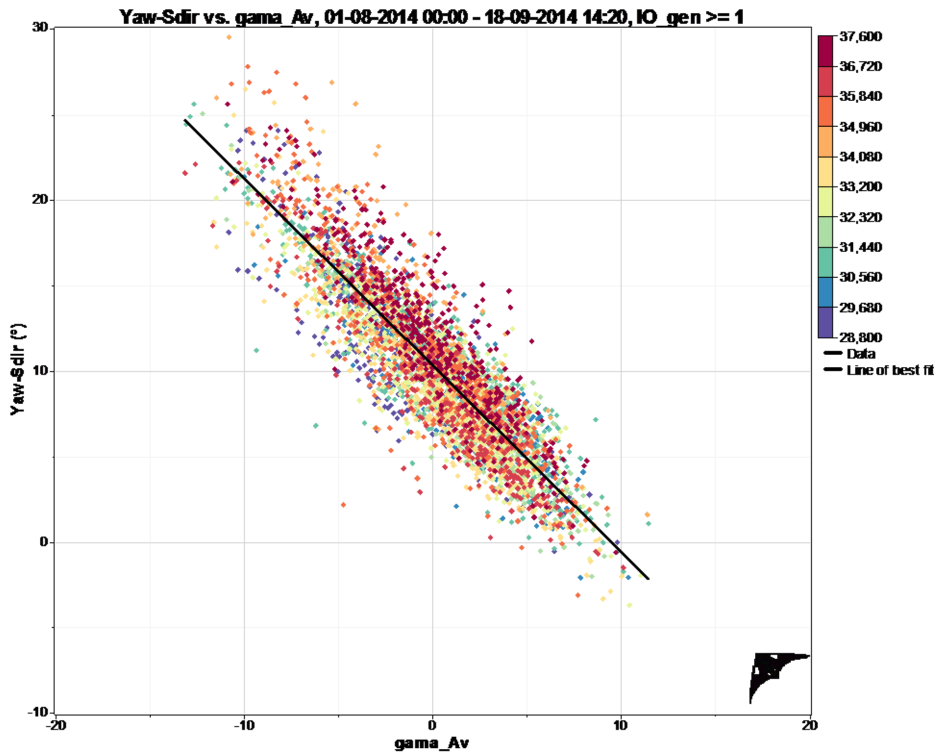


Figure 22 Scatterplot between gama_Av and the difference between yaw and sonic direction. Colorcoded by time.

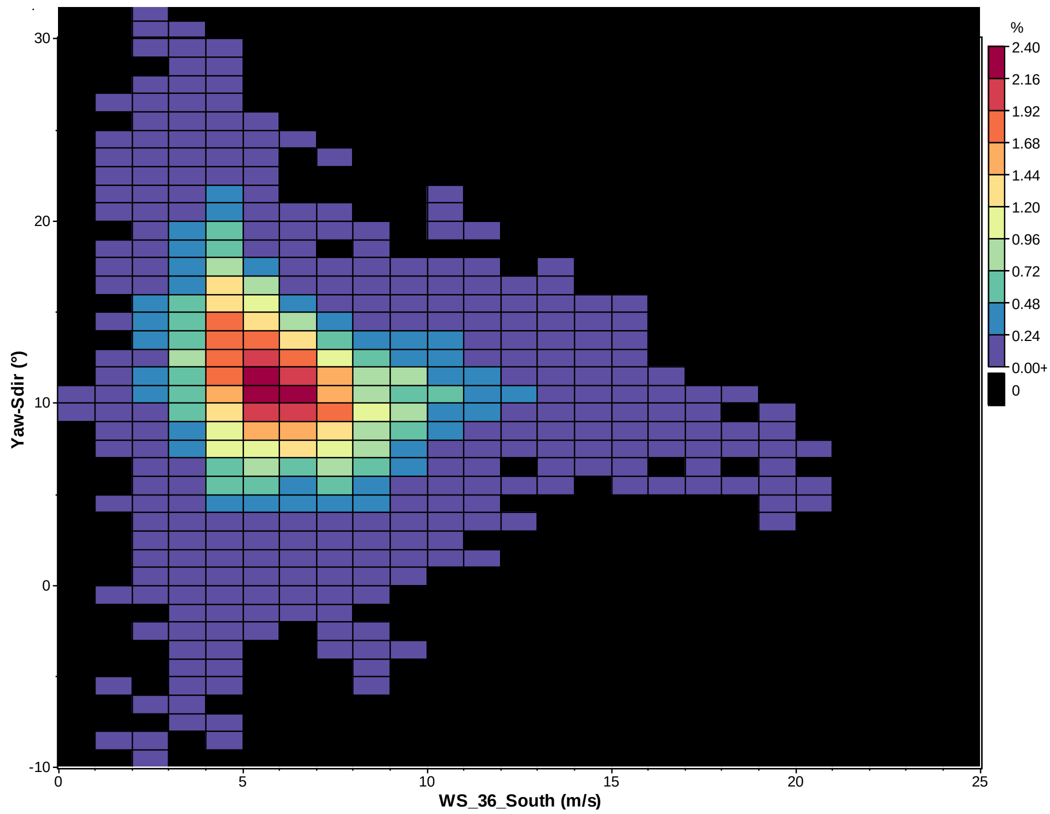


Figure 23 Density plot of difference between yaw and sonic direction as function of wind speed. Colors indicates the frequency of occurrence.

Due to these findings, it has been considered necessary to assess the yaw signal accuracy. To do that a technician climbed the turbine and, by overriding manually the wind turbine control system pointed the nacelle in 5 different points well visible over the horizon. The table below shows the yaw readings from the acquisition system and heading values found form google earth. The two measurements agree very well and do not show any error on the calibration of the Yaw signal as can be seen in the following table.

Table 6 Comparison of turbine yaw reading and Google Earth direction

	daqwin	google earth
met tower	285.85	285.37
risø met tower	334.96	334.27
water tower	34.69	33.92
kara chimney	162.52	162.22
cathedral	192.86	192.9

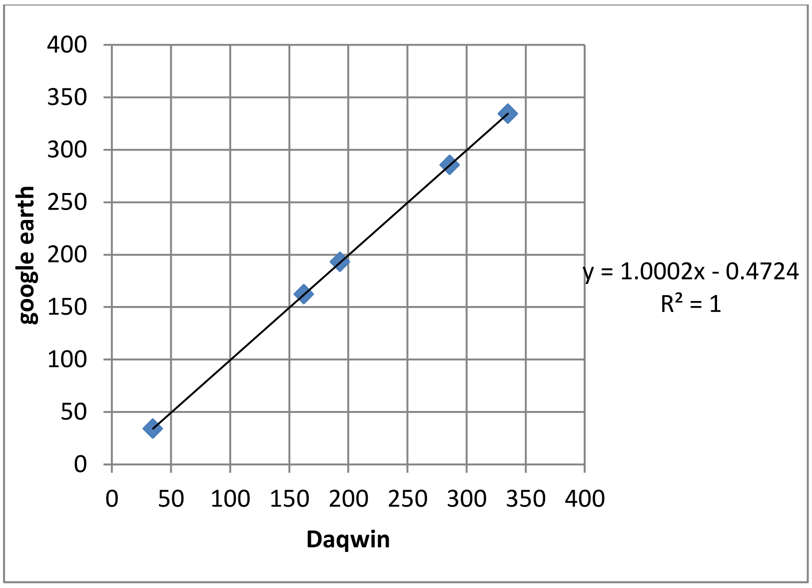
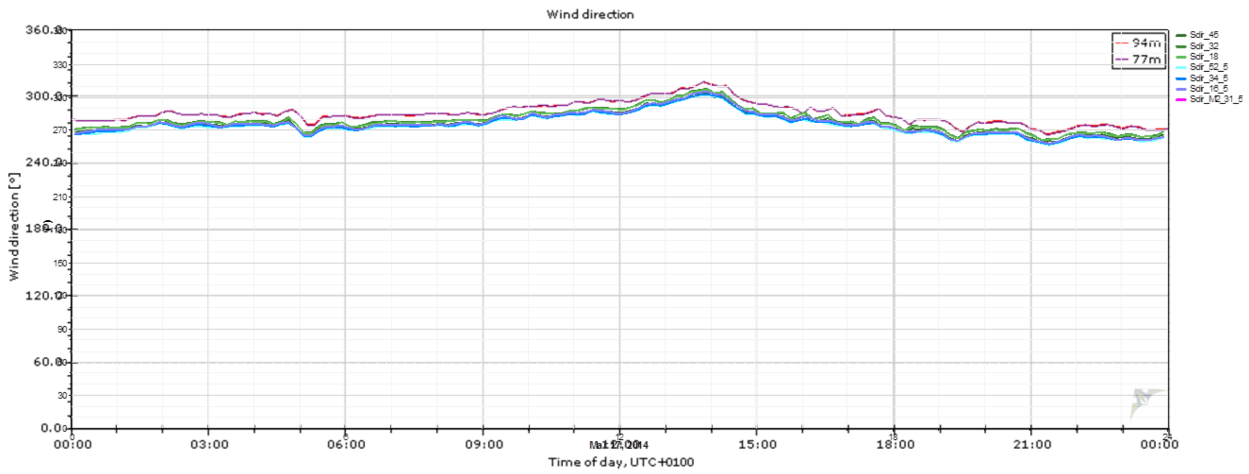


Figure 24 Scatterplot and regression line between yaw readings and heading values form google earth. Unit is Degrees.

After assessing the accuracy of the yaw, the focus was switched to the met mast direction measurements. The Metek 3D sonic anemometers are mounted on booms with instrument north aligned to the boom through a pin. The direction between the boom and the north serves as a offset that is defined in the acquisition system. This offset is set to 18 degrees and the boom heading has been verified with a compass giving 16 degrees.

Last investigation was performed by comparing all masts direction measurements available at Risø campus. The direction measurements from the tall and short Nordtank mast where plotted together with the direction measurements from the met mast in front of the V27 turbine and the Risø met tower. The V27 met mast is a tower installed in front of a Vestas V27turbine existing in the same area where the Nortank turbine is. 127 m separate the V27 mast to the Nordtank tall mast. The main Risø tower is located a bit further away down near the fjord (1.2 Km) but still considered representative for wind direction comparisons. Wind direction is measured using sonic anemometers at the V27 mast and with wind vanes at the Risø tower. The following graph shows westerly and southerly wind direction measurements for 1 day from all the 7 sonic anemometers. Days with wind speeds below 5 m/s and stable atmosphere have been avoided. Figure 13 shows roughly a 10 degree difference between the wind direction measured at the Risø met tower (at 94m and 77m) and that measured at the Nordtank mast. There is also a small difference between the Nordtank and the V27 direction measurements of roughly 3-4 degrees. Due to the technical difficulties in anemometers mounting on towers deviation of such magnitude should be expected. Such differences seem to increase for southerly winds. Easterly and Northerly winds have not been considered due to data affected by turbines wakes. Wind vanes mounting have not been verified yet at Risø tower. Still it is not clear what is the reason for such 10 degrees difference.



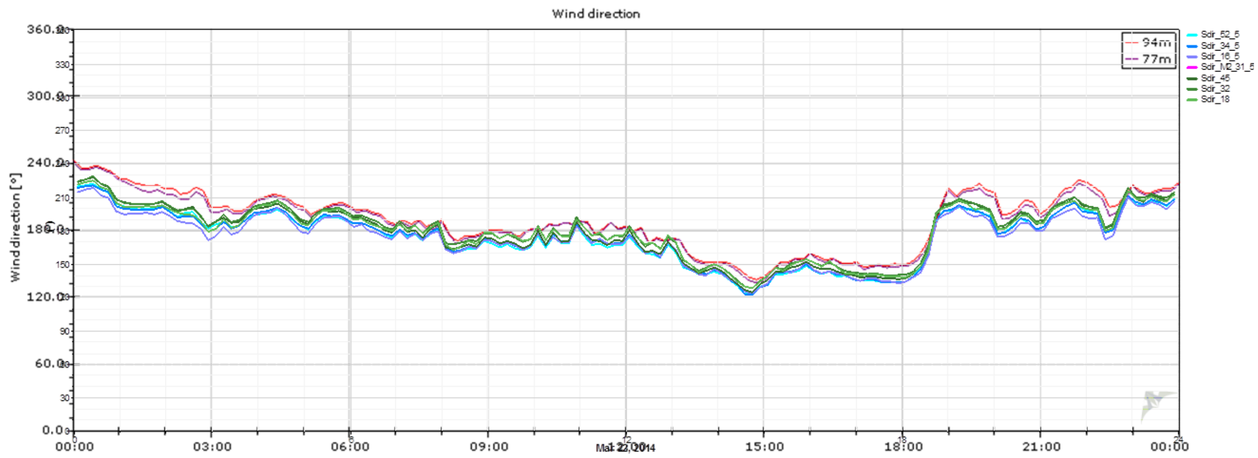


Figure 25 Comparison of all mast wind directions measurements existing at ~~r~~Risø campus. ~~Green~~ V27 mast direction measurements in green scale, Nordtank tall mast in blue scale, s~~S~~mall mast in purple (no data) while the Risø Tower wind vanes measurements are in legend without the "Sdir" prefix during the 17 (upper) and 22 of March (lower) 2014, two recent days where the wind has been blowing all day from mast-turbine direction.

8. Synchronization

Synchronization between masts and turbine measurements is assured by having the same acquisition system recording all the signals.

The Daqwin software organizes every 10 minutes measurements in "blocks". Every block has a name given by the windows clock time. Such clock time is also the one found in the time stamp filed in the database. Unfortunately the first sample at 35 hz does not always corresponds with the the beginning of the 10 minutes periods and such data can be acquired with quite some lag of even of few seconds. Such lag is also not constant and can increase or reduce in time.

In order to make comparisons with fast data measured by other systems, the DAQwin was configured to measure the windows clock for every sample. The windows clock is synchronized to the Risø time server ntp.risø.dk. Unfortunately sub seconds time measurements were not allowed due to Windows limitations. This means that we are sure of the synchronization within 1 seconds but not shorter time scale

9. Wind conditions during MC1

Data have been analyzed to provide an overview of the wind conditions measured in the period 5.8.2014 (spinner lidar installed) to 1.10.2014(spinner lidar removed)

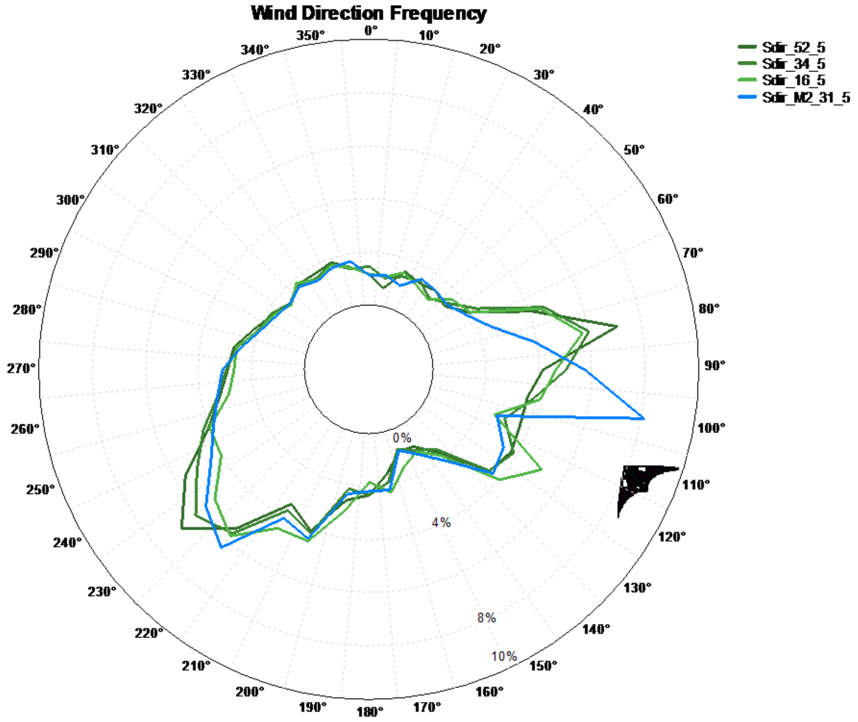


Figure 26 Frequency by direction

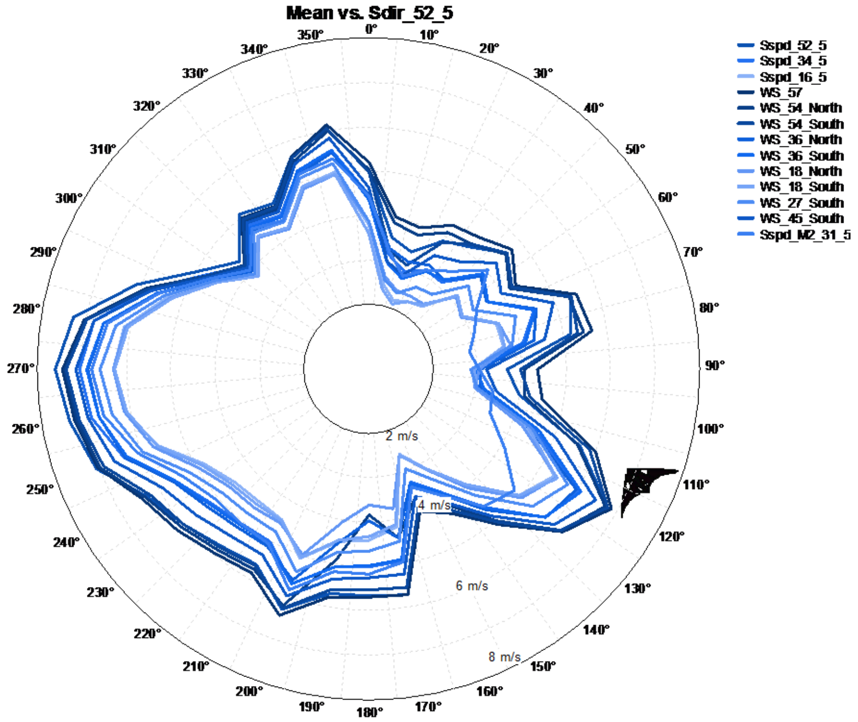


Figure 27 Mean wind speed by direction

Only data from westerly sectors have been considerd for the following graphs.

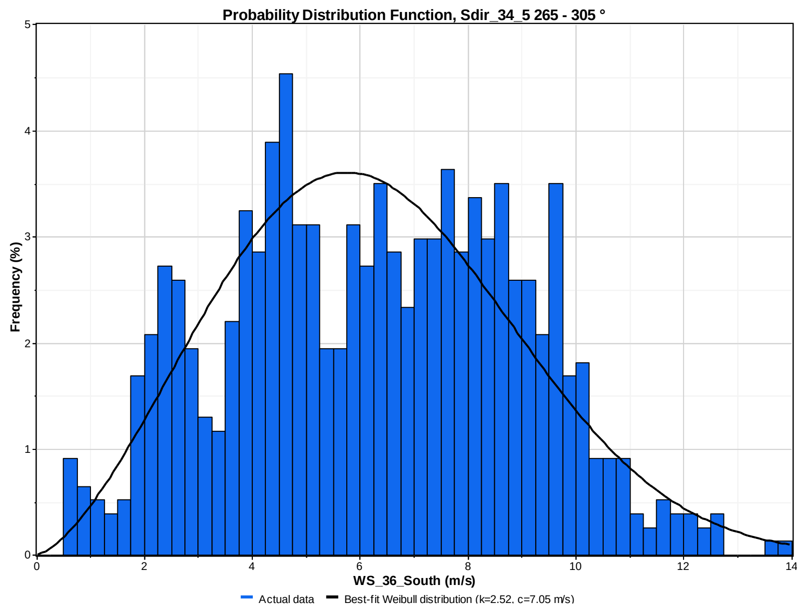


Figure 28 Speed frequencies

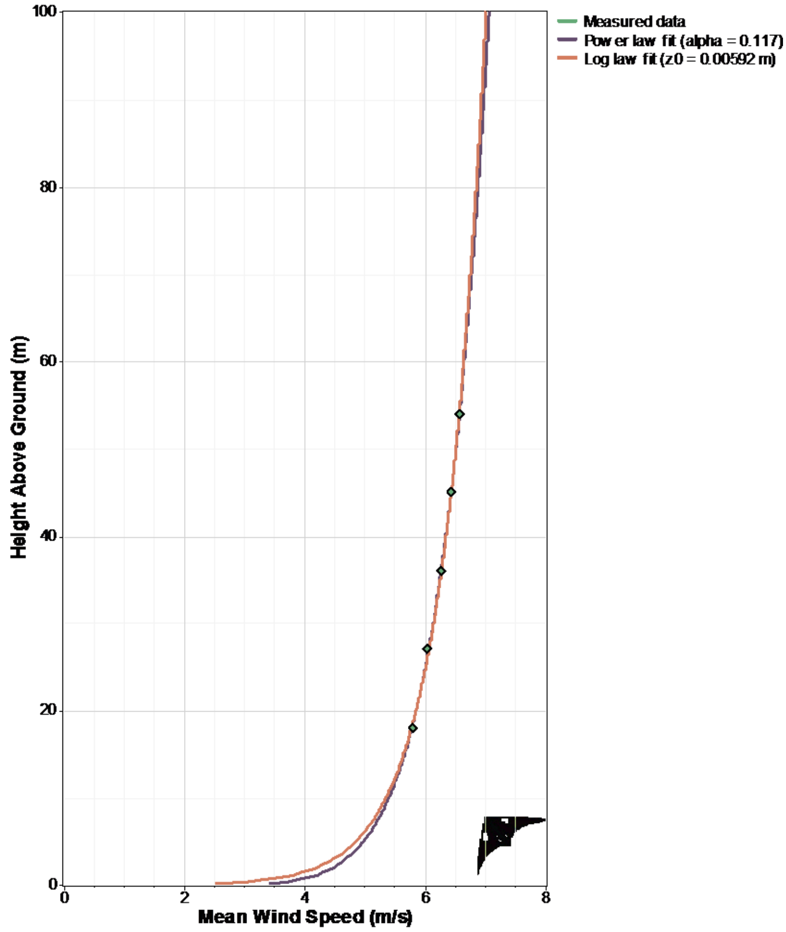


Figure 29 Mean vertical wind shear

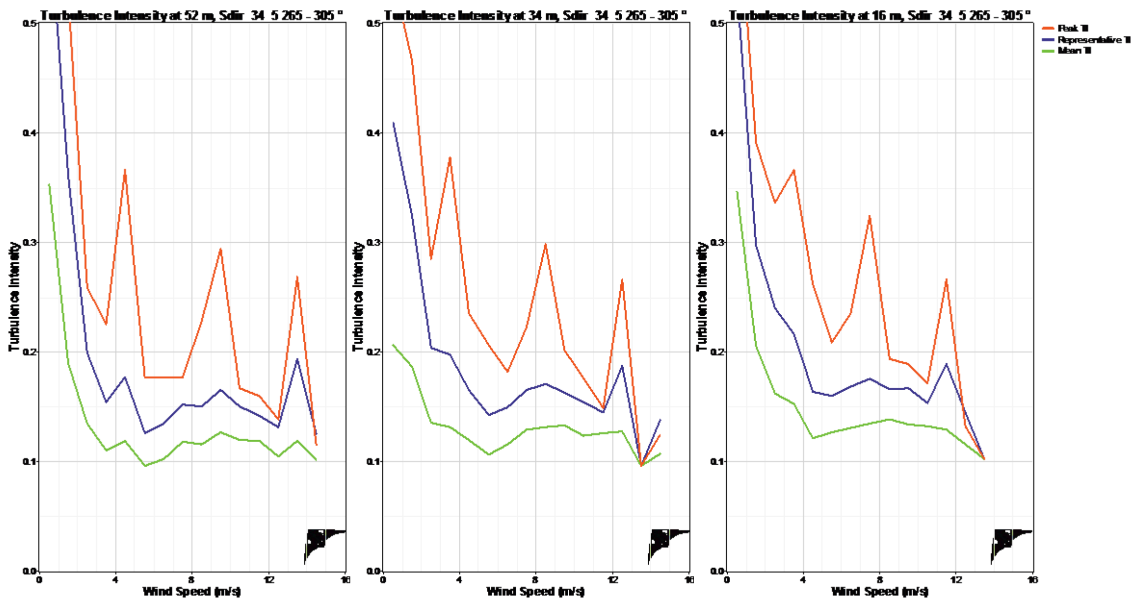
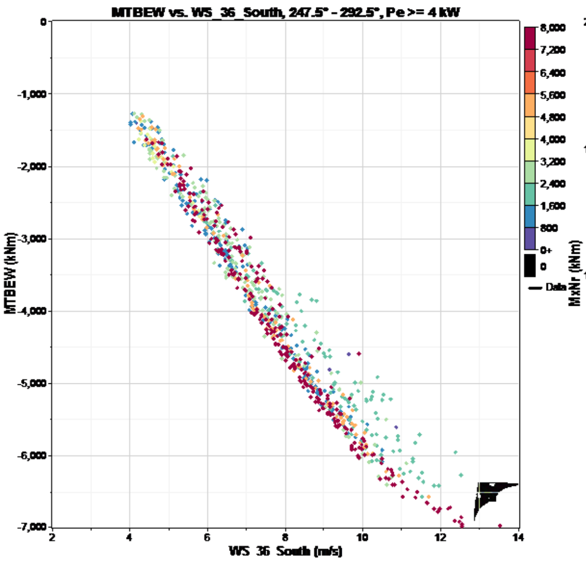


Figure 30 Mean, representative (90th quantile) and peak (max in wind speed bin) turbulence intensity at three heights.

Behavior in function of wind speed of relevant parameters measured at the turbine is shown in the following graphs. The points in the scatterplots are colored in function of record number who is a proxy to indicate time.



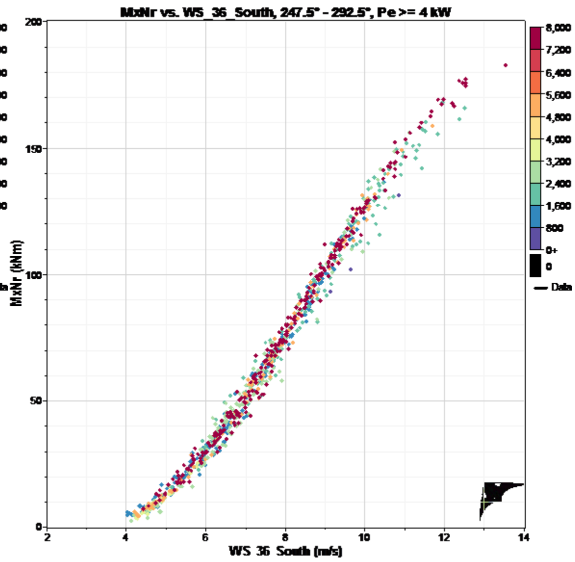


Figure 31Tower bottom moment East West direction (Left) Shaft torsion (right)

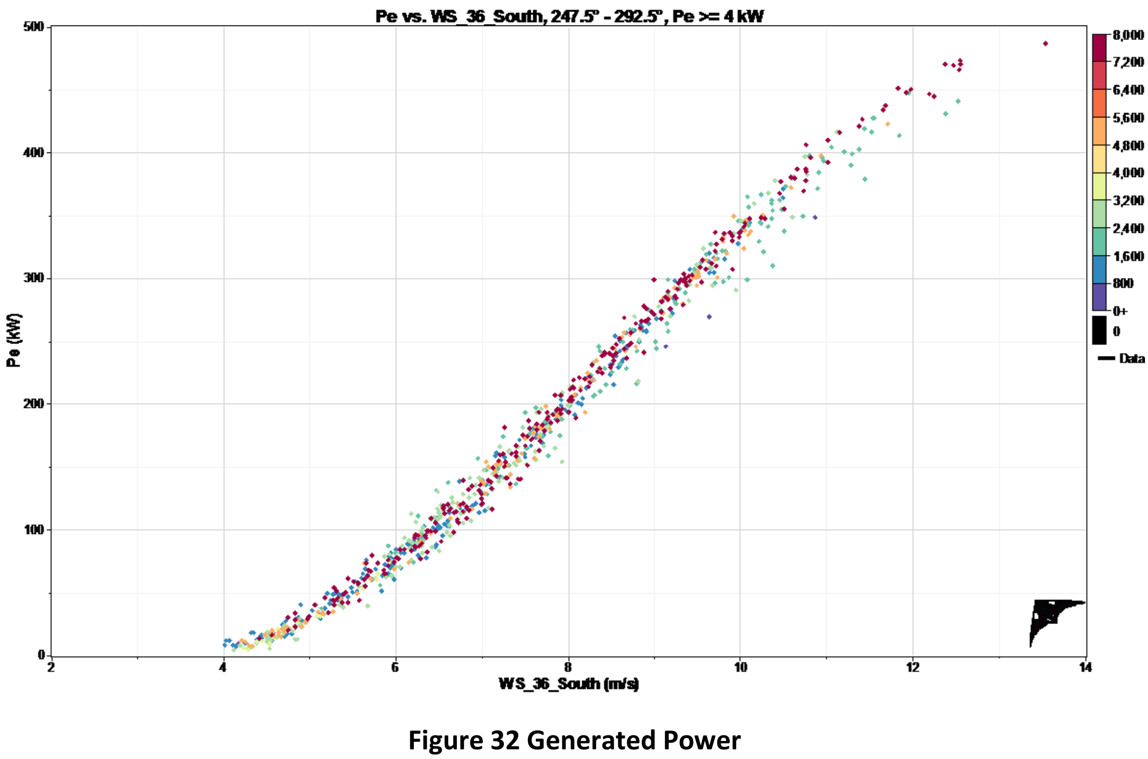


Figure 32 Generated Power

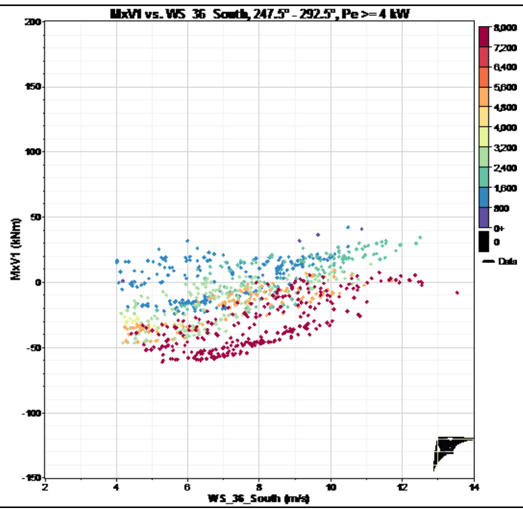
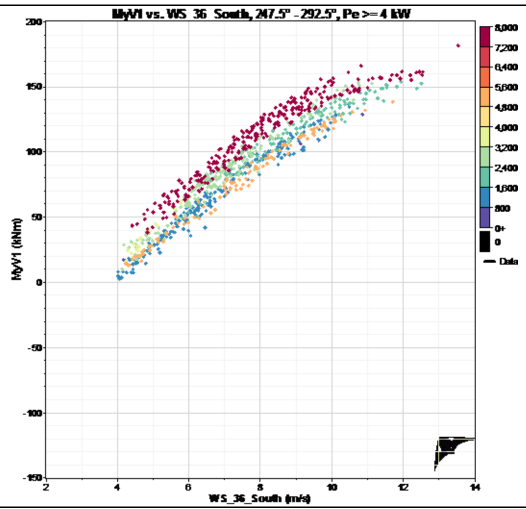
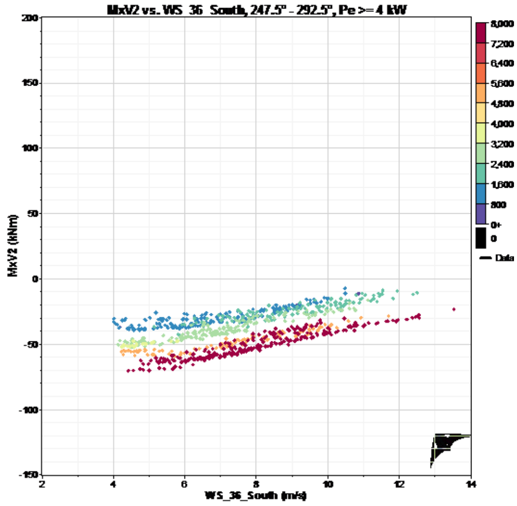
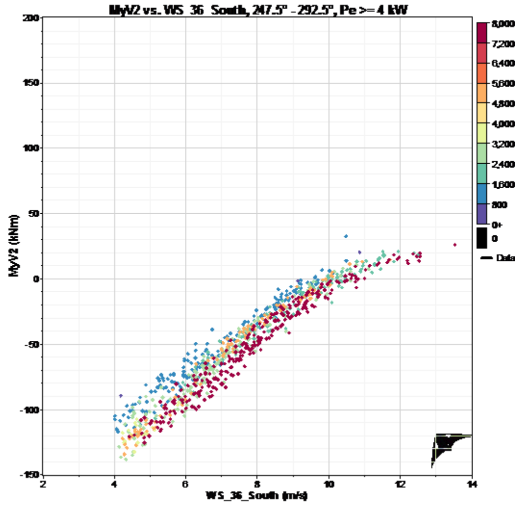
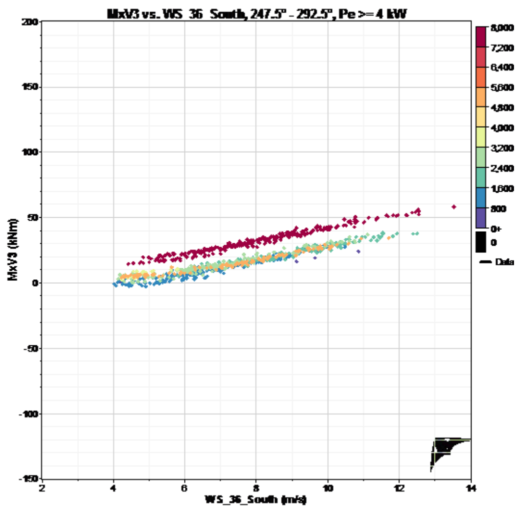
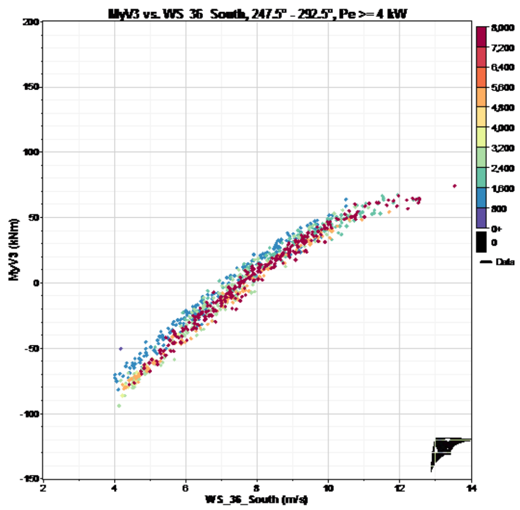
	Edgewise	Flapwise
Blade1		
Blade2		
Blade3		

Figure 33 Ten minutes averages of blade root bending moments versus wind speed

A certain degree of drift can be noted by looking at the graphs above, especially on the strain gauge measuring the edgewise moment on blade 3. By color-coding the points in the scatterplot it is possible to easily identify that the drift has been sudden for this channel while all the others show a more gradual drift in time. It is important to remember that the strain gauges are mounted on the outside of the blade root and they are prone to water infiltration. The possible cause of such a drift could be a rainy period without wind where the turbine rotor was stopped for almost 2 days with blade 3 in a position where the gravitational force was creating a constant moment (Figure 34). In such conditions the strain gauge could have been stretched or compressed in a way to change its response. Since the event has been sudden and not linear over time, it is difficult to correct for it. Basically a new blade pull is required every time drift occurs, which was not possible in the budget of UniTTe for MC1.

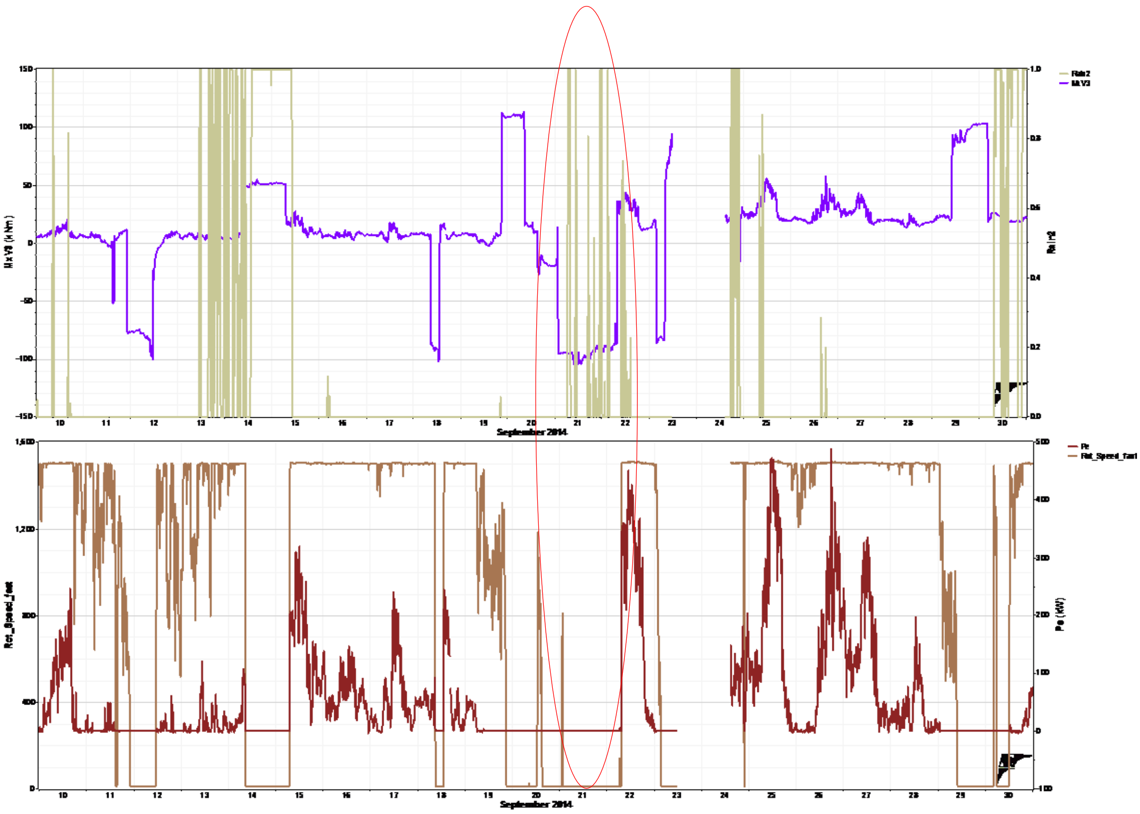


Figure 34 . Top graph shows edgewise bending moment in blue and precipitation. The lower graph shows power in red and rotor speed in brown.

10. Thrust curve analysis

The axial wind forces applied on the rotor of the turbine creates bending moments on the tower

and the foundations. Using strain gauges, the bending moments can be recorded at any position on the tower. Therefore, it should be possible to measure the bending moments generated by the thrust on the tower, and ultimately to derive the thrust itself from these measurements.

The mass of the wind turbine contributes to the bending of the tower by applying a moment at

its top. This moment is roughly equal to the mass of the rotor multiplied by the shaft length (more precisely to the distance between the rotor position, and the center of the tower), and by the gravity constant g.

$$BM_{Rotor} = -M_{rotor} \cdot L_{shaft} \cdot g$$

The wind is also acting on the tower and is creating a corresponding bending moment at the tower bottom. As the force is distributed over the section area of the tower, it is integrated to derive the bending moment. The formula is therefore the integral of the force acting on an infinitesimal area of the tower multiplied by the distance from the strain gauge. As the tower radius decreases significantly over the tower height (from R0 to RHub), this is taken into account by assuming a linear decrease of the tower radius

$$\overrightarrow{BM_{Tower}} = \frac{1}{12\,H_{Hub}} \cdot \pi\,\rho C_D U^2 \left(H_{Hub} - H_{SG}\right)^2 \left(H_{Hub}\left(2R_{Hub} + R_0\right) + H_{SG}\left(R_{Hub} - R_0\right)\right)$$

Finally, the tilt moment of the turbine can also influence the bending moment measured on the tower. In fact, the difference of wind speed between the upper part and the lower part of the rotor can create a moment applied on the shaft at the connection with the rotor. This moment is propagated to the bottom of the tower where it is added up to the other contributions. This contribution is the smallest and is not considered in this analysis.

The thrust is only one component of various moments created by the complex interaction between the wind flow field, the gravity field and the turbine. A model taking into account the major moments applied on the tower is therefore needed to be able to derive the thrust from strain gauges measurements.

The model used is based on measurements of two strain gauges including information of wind direction, as suggested in [7].

$$Thrust_2 = \frac{1}{H_{Hub} - H_{SG}} \left(\frac{SG_1 \sin\left(\theta_{wind} - \alpha_2\right) - SG_2 \sin\left(\theta_{wind} - \alpha_1\right)}{\sin\left(\alpha_1 - \alpha_2\right)} - BM_{Rotor} - BM_{Tilt} - BM_{Tower} \right)$$

The meaning of the acronym explained in the following figure

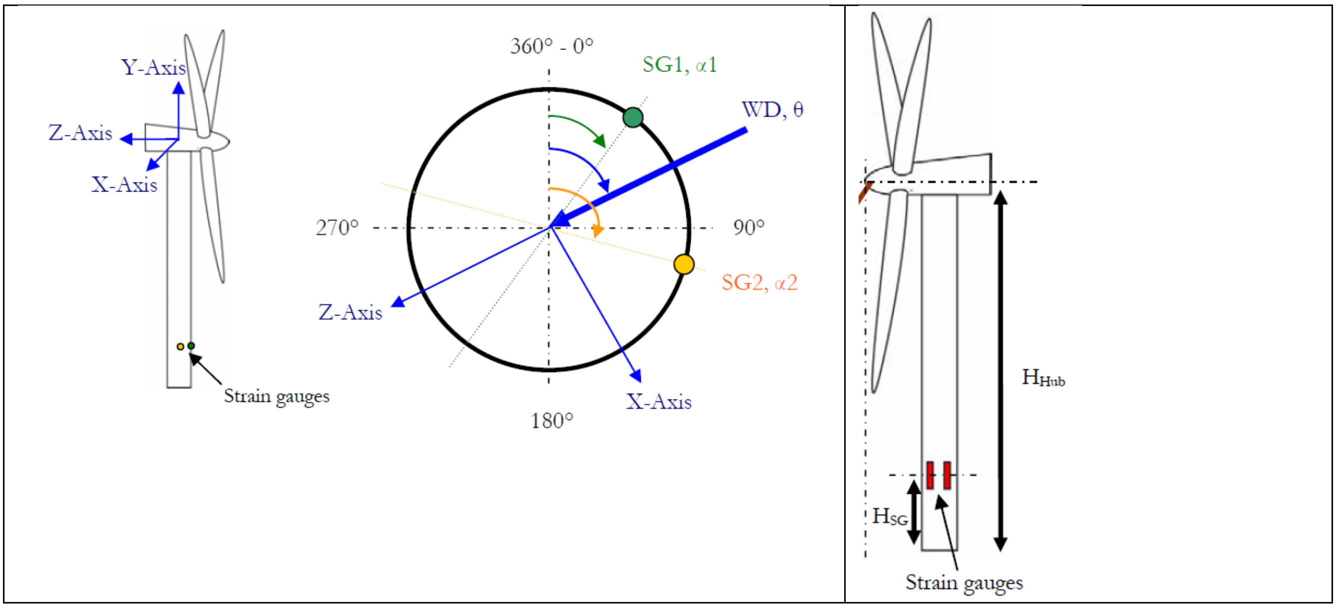


Figure 35 Explanation of variables used in the model applied to derive thrust from strain gauges measurements.

By assuming small changes of wind direction in the 10 minutes period the formula above has been applied to 10 minutes averages go the values required. A scatterplot of 10 minutes values and bin averaged thrust in function of wind speed can be seen in Figure 36 where it is compared to the thrust curve made available by the turbine manufacture in wind resource assessment software. In this case WindPro.

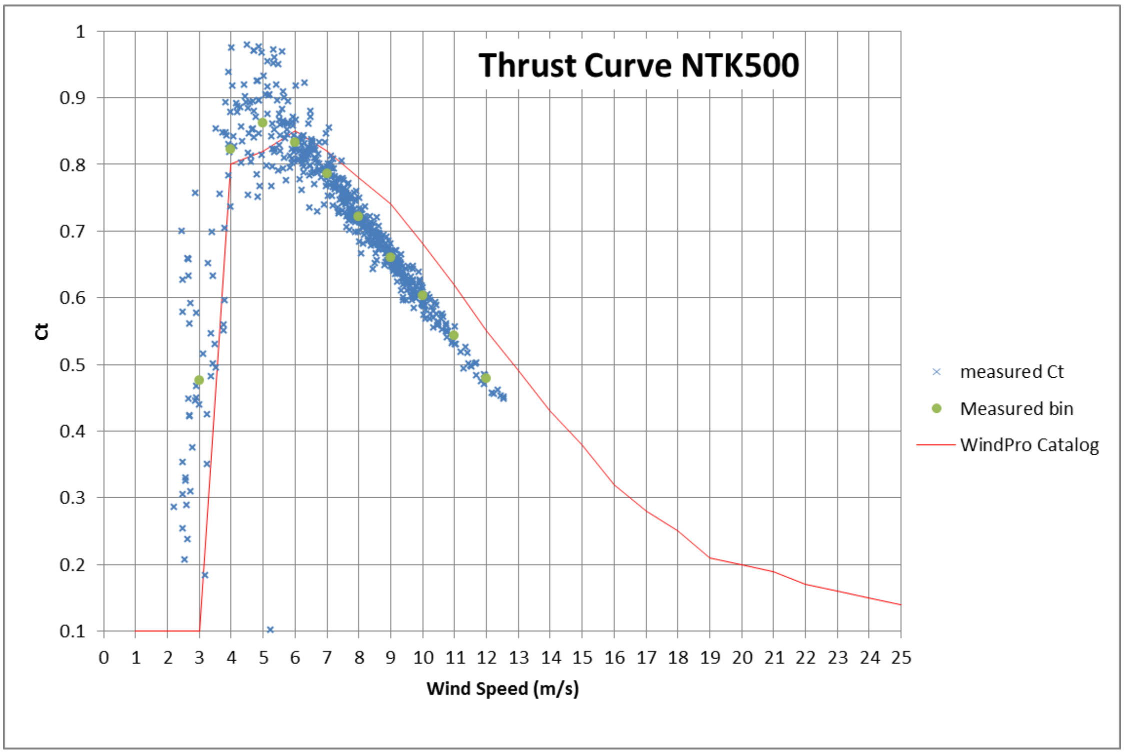


Figure 36 Thurst in function of wind speed

References

[1] Measuring the inflow towards a Nordtank 500kW turbine using three short-range WindScanners and one SpinnerLidar, (DTU Wind Energy E; No. 0093) Nikolas Angelou and Mikael Sjöholm, September 2015

[2]IMPER: Characterization of the Wind Field over a Large Wind Turbine Rotor : Final report. / Schmidt Paulsen, Uwe; Wagner, Rozenn. Wind Energy Department, Technical University of Denmark, 2012. 335 p. (DTU Wind Energy E; No. 0002). Research › Report – Annual report year: 2012

[3] IEC 61400-12-1 ed.1 Wind turbine power performance testing

[4] IEC 61400-12-1 Ed.2 Draft CDV

[5] IEC TS 61400-13 ed.1 Measurement of mechanical loads

[6] Demurtas, G., & Friis Pedersen, T. (2014). Summary of the steps involved in the calibration of a Spinner anemometer. DTU Wind Energy. (DTU Wind Energy I; No. 0364).

[7] Pierre-Elouan RÉTHORÉ, s041541 “Thrust and wake of a wind turbine:Relationship and measurements”, M.Sc. thesis, September 2006

Thanks to

All the TEM technicians who helped out setting up the experiment and performing all the required verification.